U.S. Coast Guard Research and Development Center

1082 Shennecossett Road, Groton, CT 06340-6096

Report No. CG-D-01-00

MARINE FUEL CELL MARKET ANALYSIS

Final Report
September 1999

This document is available to the U.S. public through the
National Technical Information Service, Springfield, VA 22161

Prepared for:

U.S. Department of Transportation
United States Coast Guard
Operations (G-O)
Washington, DC 20593-0001

N O T I C E

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

This report does not constitute a standard, specification, or regulation.

Marc B. Mandler, Ph.D.
Technical Director
United States Coast Guard
Research & Development Center
1082 Shennecossett Road
Groton, CT 06340-6096

Technical Report Documentation Page

1. Report No.	2. Government Accession Number	3. Recipient's Catalog No.
CG-D-01-00		
4. Title and Subtitle Marine Fuel Cell Market Analysis		5. Report Date September 1999 6. Performing Organization Code Project No. 3310.2
7. Author(s) Zvi Karin, N. Leavitt (JJMA) and T. Costa, R. Grijalva (CALSTART)		8. Performing Organization Report No. R&DC-297-99
9. Performing Organization Name and Address John J. McMullen Associates, Inc. 4300 King Street, Suite 400 Alexandria, VA 22302	United States Coast Guard Research & Development Center 1082 Shennecossett Road Groton, CT 06340-6069	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTCG39-95-D-E99010 T.O. E00260
12. Sponsoring Organization Name and Address U.S. Department of Transportation United States Coast Guard Operations (G-O) Washington, DC 20593-0001		13. Type of Report & Period Covered Final 14. Sponsoring Agency Code Commandant (G-OCU) U.S. Coast Guard Headquarters Washington, DC 20593-0001

15. Supplementary Notes

The R&D Center's technical point of contact is Robert D. Sedat, 860-441-2684, email: rsedat@rdc.uscg.mil.

16. Abstract (MAXIMUM 200 WORDS)

Numerous studies have shown that it is feasible to reform diesel fuel to derive electric power from fuel cells. The improved efficiency, reduced emissions, and other attributes of fuel cells make them an attractive alternative to existing power sources. This study assesses the potential marine demand for fuel cells, and provides incentive for developers to pursue this market.

Data on 87,000 worldwide commercial ships and on the U.S. Naval fleet were analyzed to assess the market potential for marine application of two types of fuel cells. In addition, a phone survey of potential users and an international market survey report were used to complement the assessment. Independent data assessment by a European consultancy service on the expected marine market penetration of fuel cells yields similar conclusions to those developed here. Marine market penetration is expected to follow the land-based stationary and transportation application of the technology. The survey concludes that the majority of new units are concentrated below 2 MW, and amount to about 5000 new units per year. This market can potentially be penetrated by systems made up of multiple 500 kW fuel cell modules. Thus, there is substantial potential demand for fuel cells from the commercial marine sector.

17. Key Words		18. Distribution Statement	
fuel cell, marine market, marine power penetration, Molten Carbonate Fuel Cell (mcfc), Proton Exchange Membrane Fuel Cell (pemfc)		This document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161	
19. Security Class (This Report)	20. Security Class (This Page)	21. No of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	113	

Form DOT F 1700.7 (8/72) Reproduction of form and completed page is authorized.

[This page intentionally left blank]

EXECUTIVE SUMMARY

Background - Reason for this Study

In partnership with the U.S. Navy and other Federal agencies, the U.S. Coast Guard has been investigating the feasibility of using fuel cells to provide shipboard electric power. Studies have been conducted which demonstrated the feasibility of reforming marine diesel to generate electric power using current fuel cell technology. Due to their higher efficiency, fuel cells can generate power using 25-30% less fuel than existing marine diesels or gas turbines. While it appears technically feasible to implement such technology, the future development of such systems for shipboard use remains an issue.

Major fuel cell manufacturers are currently focusing development efforts on obvious land-based markets, such as automotive transportation and on-site electrical generation. Initial Navy and CG studies revealed that existing land-based fuel cell systems need to be made lighter and more compact, and to resist salt air and high shock environments, before they are suitable for marine use. Fuel cell developers are reluctant to devote scarce resources towards meeting these unique shipboard requirements until they are persuaded that a sufficiently large potential marine market exists. This report surveys the "displacement" market of existing marine diesels and gas turbines, identifies key market drivers, and establishes the size of the potential marine market for fuel cells. It describes technical targets that must be met for successful market penetration, and provides economic justification for manufacturers to develop commercially competitive shipboard fuel cell systems. The Coast Guard would benefit from the commercial availability of such systems, as they have potential to reduce fuel use and harmful emissions aboard CG cutters, and other vessels operating in the marine environment.

Study Methodology and Results

The study assesses the market potential for marine applications of molten carbonate fuel cells (MCFC) and proton exchange membrane fuel cells (PEMFC) for the years 2005, 2010 and 2015. The report summarizes the analyses by the CALSTART organization and by EscoVale, Inc.

Thirteen major market segments were identified by analyzing over 87,000 worldwide and U.S. commercial and naval ships. This group comprises approximately 93 percent of the world fleet. The marine power market is very stable and has been so over the last 38 years, the historical period surveyed. Further, power demands for these major market segments are very well structured for both propulsion and ship service generator (SSG) power. Analysis of the market segments revealed that power ratings for both propulsion and SSG were tightly clustered around specific power rating sizes for all major market segments. Many propulsion power units are rated at 2 MW and below, independent of the market segment analyzed. Thus, a large fraction of world power demand is concentrated in a few power sizes, mostly less than 2 MW.

The marine potential market for fuel cells was assessed by looking at specific ship types, including cargo vessels, container ships, oil tankers, etc., that might represent significant market segments for fuel cell power in the future. The two types of power plants considered include primary propulsion and ship service generator sets (SSG).

A large data base of ships in service and future construction was analyzed. In addition, structured interviews of naval architects, ship builders and ship owners/operators were conducted. The main goal of the survey analysis was to see if a significant market potential for fuel cell power applications could be identified for the years in the study forecast period. The objectives of the interviews were: 1) to test awareness of, and interest in, fuel cells among key stakeholders, and 2) to get a sense of what these stakeholders view as the critical factors that might influence their decision to adopt fuel cells in marine applications.

The structured interviews yielded two primary insights. First, naval architects and ship builders generally espouse a position of technology orthodoxy. Some have not considered fuel cells at all, while others are waiting to see how rapidly such propulsion systems become commercially available. Second, ship operators interviewed said that relative cost, energy efficiency, and complexity are indirectly important. The two factors that drive their acquisition choice for any new technology are as follows:

1. Increased productivity, and
2. Increased competitive advantage.

This study assumes that marine applications will lag land applications somewhat, but that some of the same economic and regulatory drivers that affect land applications will affect marine use. This study argues that marine applications will proceed in a "fast-follower" manner shortly behind land applications of fuel cells. Marine market penetration of FC technology will depend on the rate at which the fuel cells can be made technologically and economically competitive to primarily diesel engines as prime movers for propulsion and ship service generators (SSGs). Most importantly for early adopters, market penetration will depend on emerging environmental requirements (e.g., emissions credits, regions with local air quality problems, etc.).

If fuel cell technology can be made commercially justifiable with unit power output between 250kW and 500kW, the study concludes that the marine market potential for fuel cells could be tens of thousands of units sold by the year 2015. To capture a significant fraction of this potential, technical, economic and regulatory factors identified in this report must be addressed. The survey concludes that the majority of new units are concentrated below 2MW, and amount to about 5000 new units per year. This market can potentially be penetrated by systems made up of multiple 500 kW fuel cell modules.

Significance of this Study

The results of this study are favorable to the development of marine fuel cells. While fuel cells are particularly attractive for Naval applications, the vast majority of marine power demand is from commercial shipping. The study demonstrates that, if the life cycle costs of fuel cells can be made economically competitive with traditional sources of marine power, they can potentially capture a substantial marine market.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

LIST OF FIGURES

FIGURE **PAGE**

LIST OF TABLES

TABLE **PAGE**

[This page intentionally left blank]

1.0 INTRODUCTION

1.1 Background

The fuel cell, often thought of as a new technology, was actually invented in 1839 by William Grove, a British physicist/judge. The concept is centered on an electrochemical process which converts chemical energy into electrical energy, similar to the principles behind a conventional battery cell. The main difference, however, is that a fuel cell continuously produces electricity while fed fuel and oxidant, where a traditional battery is simply a storage device.

There are several types of fuel cells in existence today, each with varying features and characteristics. This report will center around the two types which are considered candidates for shipboard use, the Molten Carbonate fuel cell (MCFC) and the Proton Exchange Membrane fuel cell (PEM). The following areas of interest are discussed within the report:

- Technologies involved
- Key factors driving propulsion and auxiliary power source selection, including
  - Economic
  - Technical, and
  - Regulatory Body Compliance
- Comparison with traditional power sources (diesel engines and gas turbines)
- Potential applications in the marine industry, including
  - New-building and
  - Growth markets
- Market forecasts, and
- Associated costs.

The U.S. Navy is currently sponsoring development of both Molten Carbonate and Proton Exchange Membrane marine fuel cell power modules for the marine industry. In conjunction with the Navy, the U.S. Coast Guard has developed the ship interfaces required for a MC fuel cell installation and a dynamic simulation incorporating the MC fuel cell as the primary power provider.

This report is based primarily on CALSTART's Market Survey Report integrated with information provided by EscoVale Consultancy Services reports.

1.2 Objective

The objective of this report is to perform a market analysis to assess the applicability and market potential of two types of fuel cells for shipboard implementation in the 2005, 2010 and 2015 time periods. Over the forecast period, the U.S. Coast Guard and Navy might employ

emerging commercially viable technology if significant advantages relative to competing power sources, i.e. diesel engines and gas turbines can be attained.

Two of the main goals of this study are as follows:

1) Characterize the number of power plants that will be required in the marine market through the year 2015, and
2) Forecast the probable sizes of power units in terms of power output that will be demanded by the marketplace.

As a result of this study, the sizes of the marine fuel cell market segments, technical and economic market drivers, and numbers of units categorized by power output (kW) can be estimated.

2.0 TECHNOLOGY OVERVIEW

2.1 Fuel Cell Overview

Fuel cells as electric power generation devices are currently a relatively mature, but high-cost technology for aerospace applications. They are also emerging as land-based mobile prime movers in automobiles and buses, as well as in commercial applications for standby backup power. Demonstration units for land-based prime power applications have also been tested. These developments, as well as favorable technical and operational factors, make it attractive to consider the potential for fuel cells in naval ship and commercial marine applications for propulsion and service generators in centralized or distributed power options.

Fuel cells offer significant economic and operating potential. They are thermally efficient especially at partial loads, have inherently low vibration and noise characteristics and very low exhaust emissions.

A trend towards the design and installation of integrated electric propulsion systems (IPS) in ships has been emerging within the last decade. Many new cruise ships employ diesel generators to produce integrated propulsion and hotel power for the ships. The U.S. Navy and foreign navies are considering the use of integrated electric plants in their future planning. The implementation drivers are primarily lower life cycle cost, and flexibility in machinery arrangements that permit minimization of vibration and noise to critical areas and berthing. Commercial shippers are interested in propulsion technologies that can provide economy and reliability in their operations, while shipbuilders are primarily interested in technologies that can lower their production costs. Modular construction is an important element in shipbuilding because it can lower construction and integration complexity. Fuel cells lend themselves to modular installations and as such are expected to provide advantages in construction costs.

2.2 Technological Overview

The basic concept of the fuel cell is best visualized as the reverse of the process of electrolysis, where the passage of an electric current through an aqueous solution causes decomposition of water into hydrogen and oxygen. In the simplest form of fuel cell, hydrogen and oxygen react electrochemically, in the presence of a catalyst, to produce electricity. The fuel cell can thus be regarded as a "tertiary" battery, since it will supply electricity as long as it has a continuous source of fuel and oxidant.

Hydrogen is the ideal fuel for fuel cells, but is seldom a practical option. For example, liquid hydrogen must be stored at impracticably low temperatures just above absolute zero. Most fuel cells operate with other fuels, such as natural gas, with an initial reforming stage, to convert the fuel into a hydrogen-rich stream and to eliminate any undesirable components. Since fuel cell catalysts are intolerant of sulfur (requiring less than 100 ppb), sulfur reduction is required if diesel or similar fuels are used.

The term "fuel cell" is sometimes used to refer to an individual electrode/electrolyte assembly, and at other times to a complete power system. The simplest arrangement is that which operates on hydrogen and produces a DC electrical output. However, in practice, the system is usually fairly complex. Key components typically include: a fuel processor or

reformer; a fuel cell stack (which is typically made up of a large number of individual cells), and a power conditioner for converting the DC output of the fuel cell stack to AC power at the required voltage and frequency. Balance of plant (BOP) machinery such as pumps and blowers for fuel and air supply and process management are also required.

2.3 Fuel Cell Process Description

The fuel cell is basically a simple device combining hydrogen and oxygen to generate electricity. It consists of two electrodes, an anode and a cathode, surrounding an electrolyte. The electrolyte is a material that will allow positively charged ions to pass through while blocking the passage of electrons.

In operation, the hydrogen passes over the negative electrode (the anode) while oxygen is passed over the positive electrode (the cathode). To speed up the process, a highly conductive catalyst such as platinum or nickel, is used at the negative electrode to strip the electron from each hydrogen atom, ionizing it. The charged hydrogen ions pass through the electrolyte to the positive electrode. The electrons travel via an external circuit, where they can be used as electrical power, to the positive electrode. At the positive electrode, the hydrogen ions and electrons combine with the oxygen to produce water, a waste product. Another waste product is heat, which is generated during the electro-chemical process.

A fuel cell will provide direct current (DC) electrical power as long as it is supplied with hydrogen and oxygen. While oxygen can be obtained from the atmosphere (ambient air), the hydrogen is usually supplied from a system called a reformer. The reformer produces the hydrogen by breaking down a fossil fuel. An advantage of the fuel cell is the diversity of a suitable fuel source. Any hydrogen-rich material is a possible source ofsuitable fuel. Candidates include ammonia, fossil fuels (natural gas, petroleum distillates, liquid propane, and gasified coal), and renewable fuels (ethanol, methanol, and plant matter). A drawback to using a reformer is the release of pollutants as the system breaks down the fuel to make the hydrogen for the fuel cell. However, these pollutants are significantly lower than those produced by gas turbine or diesel generator.

As a fuel cell's electrical output is direct current (DC), an inverter is required to convert the power to alternating current (AC) to use the power generated. However, in both the reformer (converting the fuel) and the inverter (converting the electrical power) power is lost through parasitic heat losses. Thus, even though a fuel cell can have a fuel-to-electricity efficiency of 45 percent, energy losses in the reformer and inverter can decrease the overall efficiency by approximately 5 percent, to about 40 percent. By recovering the waste heat losses by heating water or air, improving the conversion process, and limiting heat losses, the efficiency of the fuel cell can be significantly enhanced.

Fuel cells are referred to by the type of electrolyte used within the system. Currently there are five main types of cells being developed/produced in the stationary fuel cell market. These are the phosphoric acid fuel cell (PAFC), the proton-exchange membrane fuel cell (PEM), the molten carbonate fuel cell (MCFC), solid-oxide ceramic fuel cell (SOFC), and the alkaline fuel cell. Alkaline fuel cells have a relatively long history in exotic uses, such as providing

electricity and water for the space shuttle due to their having fuel-to-electricity efficiencies as high as 70 percent. However their very high cost and other concerns have kept them out of the mainstream commercial market. Table 1 provides a quick overview of the four main types of fuel cells being developed for the commercial market.

Table 1. Comparison of Fuel Cells

	FUEL CELL TYPE (by Electrolyte)			
	Phosphoric Acid (PACF)	**Proton-Exchange Membrane (PEM)**	**Molten Carbonate (MCFC)**	**Solid-Oxide Ceramic (SOFC)**
Operating Temperature	Around 200° C	80° C	650° C	800-1000° C
Charge Carrier	Hydrogen ion	Hydrogen ion	Hydrogen ion	Hydrogen ion
Reformer	External	External	Internal or External	Internal or External
Prime Cell Components	Graphite based	Carbon based	Stainless steel	Ceramic
Catalyst	Platinum	Platinum	Nickel	Perovskites (Titanate of calcium)
Efficiency (percent)	40 - 50	40 - 50	Greater than 60	Greater than 60
Status of Development	Commercial systems operating, most are 200 kW; 11 MW model tested	Demonstration systems up to 50 kW; 250-kW units expected in next few years	Demonstration systems up to 2 MW	Units up to 100 kW demonstrated

Source: Lloyd, (1999, July) The Power Plant in Your Basement, Scientific American

2.4 Molten Carbonate Fuel Cell (MCFC)

The MCFC is a second generation, high temperature fuel cell technology. It employs a molten salt electrolyte and operates at 650° C. This allows for internal (or partial internal) reforming of natural gas. Due to its operating temperature, the MCFC offers waste heat which can be used for cogeneration, or which lends itself to system integration with turbine power plants. Thermal efficiencies of 40-50 percent (Allen, et al. 1998) to greater then 60 percent (Lloyd, 1999) may be achievable with MCFC technology

A 500 kW typical molten carbonate fuel cell (MCFC) process depicted in Figure 1 shows desulfurized fuel being delivered to the fuel cell power plant, mixed with steam, heated, and sent to a pre-reformer in which the fuel is then converted to methane and hydrogen. Part of the converted fuel stream is then recycled by a steam driven ejector. The remaining converted fuel is again heated and sent to the fuel cell's anodes, where methane is converted to hydrogen. The hydrogen then reacts electrochemically to produce DC current, within the fuel cell stack. A portion of the unused hydrogen, along with water and CO_2 generated within the cells, flows to a

water recovery subsystem where the water is recovered for later use. The recovered water then flows to a boiler where steam is generated for use with internal fuel cell components.

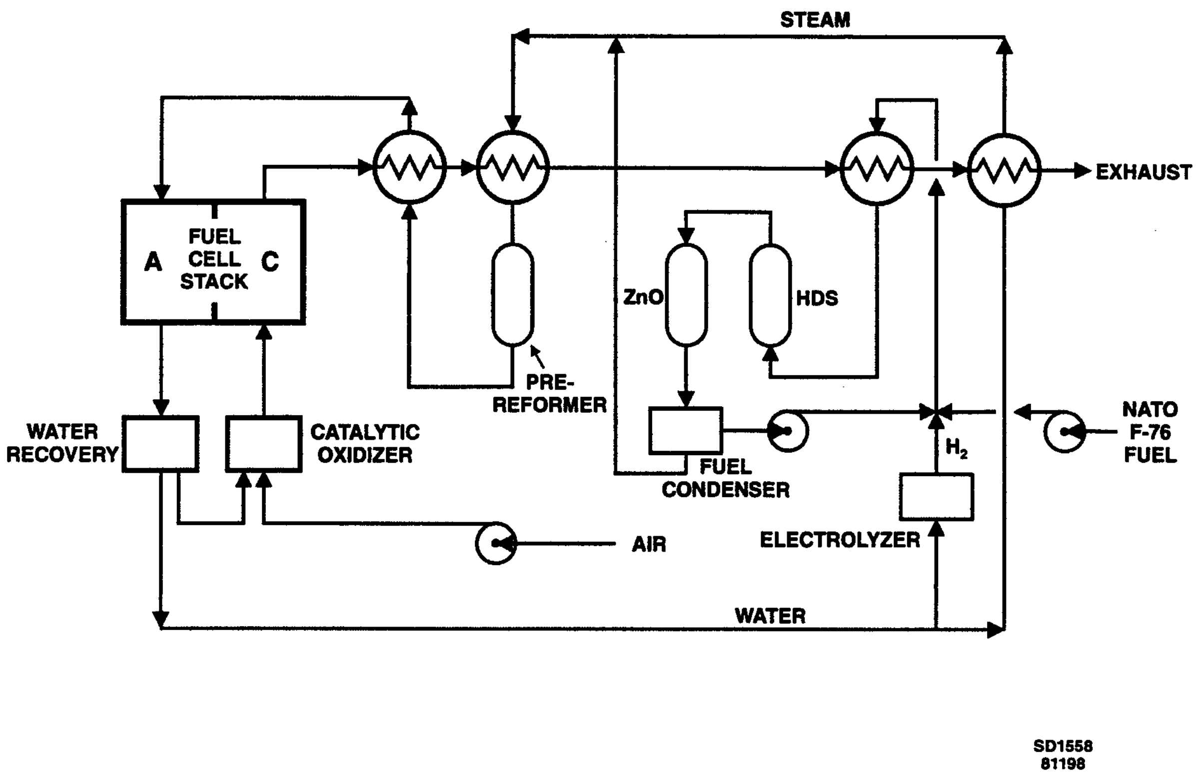


Figure 1. MCFC Fuel Cell Power Plant Process with Desulfurization (Simplified)
Source: ERC Inc., July 1999

Process air is supplied by a blower to a catalytic oxidizer, where it is heated by a reaction process using excess fuel from the fuel cell anodes. The air stream is then sent to the fuel cell cathodes, where oxygen from the atmosphere and CO_2 from the anodes facilitate the fuel cell electrochemical reaction.

Technical challenges associated with the MCFC include the corrosive nature of the electrolyte and its leakage over a period of time. Other problems include nickel dissolution and the depletion of carbonate ions that must be offset by supplementing the air supply with carbon dioxide. The latter adds cost and complexity to the system, and may involve separation of carbon dioxide from the anode exhaust gas. This is a desirable objective, but it has yet to be demonstrated under practical conditions. It is claimed that solutions to these and other difficulties are in sight, but there is still considerable work to do before lifetimes of 40,000 hours can be realized, the desired life span for a stationary commercial product. To date, endurance testing has reached 5,000-10,000 hours.

It is generally considered that commercial units are unlikely to emerge below a lower power limit (say 200 kW or 500 kW), because the MCFC tends to be inherently complex. Hence, most of the demonstrations are aiming to move up from this general area to the megawatt or multi-MW power range. In general, the MCFC is seen as one of the best technologies for larger

scale fuel cell power generation. The likelihood of MC fuel cells commercially available, based on data in the EscoVale Reports, is shown in Figure 2.

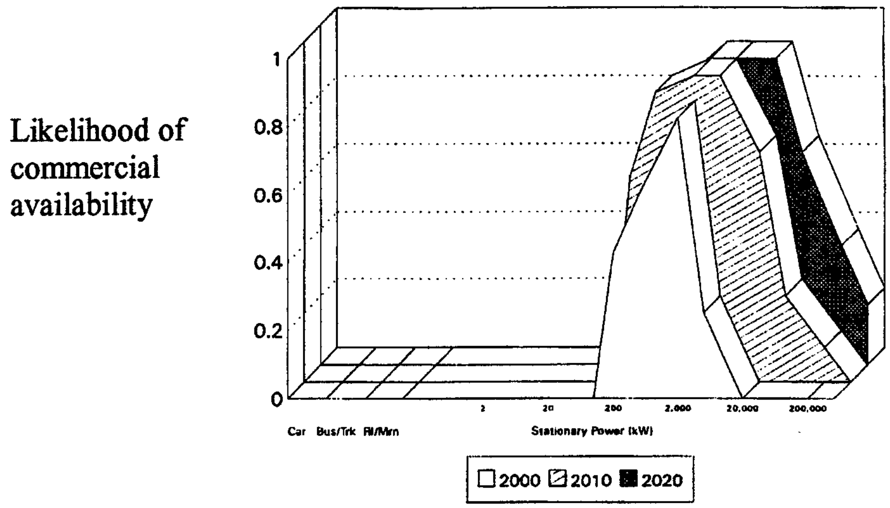


Figure 2. MCFC Prospects for Commercial Availability
Source: EscoVale Consultancy Services Report No. 5010

2.5 Proton Exchange Membrane Fuel Cell (PEMFC)

The PEMFC (also known as Solid Polymer Fuel Cell - SPFC) is a highly developed fuel cell variant that has been typically used for military and space applications and vehicular transportation applications. It is a low temperature fuel cell technology employing platinum as a catalyst and operating approximately 80° C. As in all fuel cells, fuel is supplied to the anode and oxidant air is provided to the cathode. In the PEMFC, the electrolyte separating the anode and cathode is a proton exchange membrane and is the key component of the PEM system. It is a thin, semipermeable membrane that allows positively charged particles, such as hydrogen ions, to pass through the membrane, but not electrons and atoms. This material is a synthetic polymer such as Gore-Tex or Du Pont's Nafion. Particles of platinum used as the catalyst are as small as 10 atoms in diameter and are deposited on the surface of fine particles of carbon.

The advantages of a PEMFC include high power density and the lack of a corrosive liquid electrolyte. The disadvantages, however, include the very limited CO tolerance and the requirement for careful water management to prevent membrane shrinkage and loss of ionic conduction, which also imposes limits on the operating temperature. The PEMFC operating temperatures of approximately 80° C are advantageous from a material/operating standpoint, but results in lower thermal efficiency. Thermal efficiencies in the 39-42 percent (Allen, et al. 1998) and 40-50 percent (Lloyd, 1999) range are quoted in literature. By comparison, the molten carbonate fuel cell operating at 650° C yields efficiencies in the range of 40 percent to 50 percent (see paragraph 2.4). The PEMFC is sometimes regarded as a technology, which will take longer to commercialize than most other fuel cell types. As a result, this technology will generally be confined to specialized areas. In practice, it is a well-proven technology with reasonably well

defined routes to achieving the cost reductions which will undoubtedly be required to achieve full commercial status.

2.5.1 PEMFC Applications

The main focus for PEMFC use is on transportation, however stationary applications are also receiving considerable attention. It is worth noting that many of those actively involved in PEMFCs envision earlier and more extensive deployment in the cogeneration/stationary power industries than is generally acknowledged by others fuel cell developers, specifically on small-and medium-scale plant (tens and hundreds of kW). Some envision involvement at the multi-MW level, but, as reported in the EscoVale Reports (see Figure 3), the prospects are seen as much less favorable. Other opportunities for PEMFCs are to be found at the lowest power levels (from a few watts to kW). It is, for example, the front-runner in applications such as mobile/military communications and laptop computers where fuel cells are being considered for use as an alternative to batteries. The PEMFC is also seen as a contender in applications where the alternative would be a small engine-generator set and in prospective new markets such as residential cogeneration.

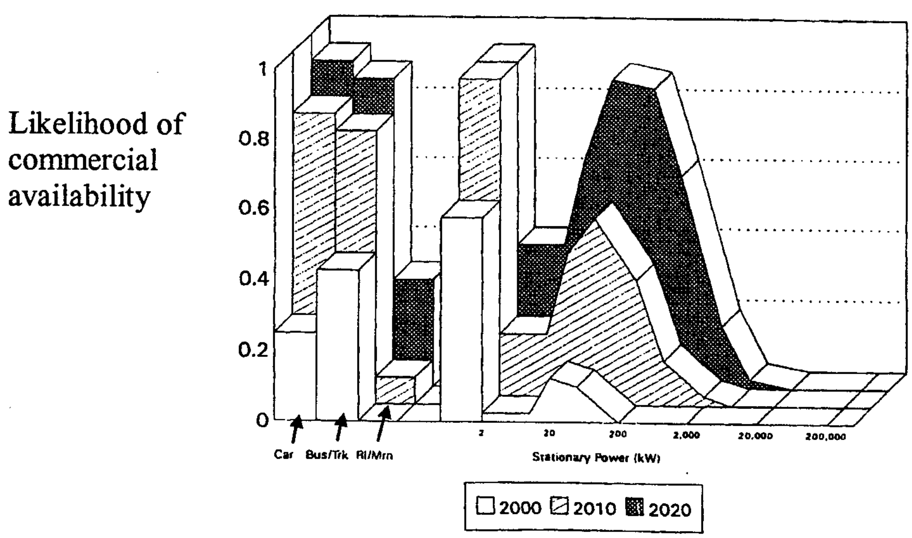


Figure 3. PEMFC Prospects for Commercial Availability
Source: EscoVale Consultancy Services Report No. 5010

2.5.2 PEMFC in Automotive Vehicles

In the past 10 years, fuel cells have undergone substantial development by a number of organizations under a variety of public sector and private sector initiatives, worldwide. As recently as five years ago, fuel cells were thought by some to be a technology that would not be commercially available for 20 or 30 years. Today fuel cells are regarded by many as being 5 years from commercial production. Recently both DaimlerChrysler and General Motors have announced that they will make fuel cell passenger cars for the mass market by 2004 and the London-based company Zevco is planning to build fuel cells for commercial vehicles in New York. In land transport applications, fuel cells offer the potential range of

conventional gasoline-powered vehicles and the emission benefits of electric vehicles. In its basic form, the fuel cell vehicle offers emissions of only heat and water.

The two major barriers to fuel cell commercialization have been its large size and high cost. The size is dependent of the structure of the electrodes and the plates separating the electrodes and required auxiliary equipment such as heat exchanger, central electrical system, fuel storage system/tank, etc. The issue of the high cost of platinum, the amount of platinum required, and the high cost of the electrolyte membrane have been the major factors in holding back commercial development of PEMFC's. Recently there have been significant developments in reducing the cost and size of PEM units for use in automobiles. These include the reduction of the cost of producing the electrolyte for the PEM; the development of catalysts more resistant to degradation from carbon monoxide developed by reformers; and improvements in the structure of electrodes and in the way platinum is used thus reducing the amount of platinum required. DaimlerChrysler recently demonstrated that size is no longer an issue when it developed a compact fuel cell for its NeCar 4, the first derivable fuel cell car in the U.S. The issue of high cost is yet to be overcome, but results appear to be promising. For example, Du Pont has stated that a total production run of 250,000 fuel cell vehicles a year would lower electrolyte membrane cost almost 10-fold. Further it is believed that continued improvements in the way platinum is used might reduce the amount of the metal needed by about half in a fuel cell. It is noted that DaimlerChrysler has stated that it expects to have fuel cell vehicles in limited production in 2004.

A third significant challenge is that of infrastructure. Various fuels can act as feedstocks for various types of fuel cells. The different systems that utilize various fuels also have tradeoffs regarding system design and ease of refueling. As a practical matter, a degree of standardization regarding feedstocks and fuel cell types must be attained before an infrastructure can be put in place that will support widespread use of fuel cells in land transport applications.

At present, fuel cells are being used in several demonstration projects around the U. S. and around the world. For example, the Chicago Transit Authority uses three hydrogen fuel cell powered buses in its daily service. Vancouver, British Columbia will soon join them with two of their own. Table 2 lists the fuel cell vehicles that are currently in prototype development. Table 2 reflects that a number of fuel cell types and applications are currently in use at the prototype stage and shows the range of traditional and new transportation technology organizations that are working on developing production versions of fuel cell land vehicles.

Table 2. On-Road Fuel Cell Vehicle Offerings

VEHICLE TYPE	MANUFACTURER	MODEL	AVAILABILITY
Passenger Car	Toyota Motor Corp.	RAV 4 - FCEV	Prototype
Passenger Car	DaimlerChrysler	NeCar 4	Prototype
Bus - Transit	Mercedes Benz (D-C)	NEBUS	Prototype
Bus - Transit	New Flyer	H40LF	Prototype
Bus - Transit	Ballard - Ford	PEM Hydrogen FC	Prototype
Bus - Transit	DOE/Georgetown	Methanol FC	Prototype
Passenger Car	Ford	P2000	Prototype
Passenger Car	General Motors	Opel Zafira	Prototype
Passenger Car (taxi)	Zevco	IPO	Prototype
Bus - Transit (40 ft.)	Nova	RTS model WFD	Prototype

Source: From Table A-10 of the LAX Master Plan, Phase III

2.6 Operating Characteristics

A particular benefit of fuel cells is their relatively simple operation. However, "balance-of-plant" (BOP) devices are needed to manage flow of fuel, air, water and exhaust, and are the only moving parts associated with the system. These support systems may be relatively complex. Fuel clean up units are required upstream of the fuel cell to desulfurize and reform the fuel as necessary. Fuel cells may also be distributed modularly throughout the ship thereby facilitating the implementation of an all-electric concept and improved survivability in the event of damage to a portion of the plant.

Start-up process is longer for the MCFC than for the PEMFC. It will take a several hours to warm up the system to more than 600° C prior to electrical load acceptance compared to minutes for the PEMCF.

Part load efficiencies of both the MCFC and the PEMFC are relatively high. This flat efficiency curve is expected to change the traditional operating mode, that of starting and stopping ship service diesel or gas turbine generators as needed to match prevailing load demands with economical operating load profiles for prime movers, to continuously operating fuel cell modules over a wide range of loads with minimal economic impacts.

These attractive operating characteristics, coupled with the expectation by industry experts that technical issues are tractable, encourage the expectation that fuel cell technology can provide a technically viable alternative to conventional fuels in the 2010 time frame. Assuming that technology issues can be addressed successfully, the question of market potential size becomes a key determinant of fuel cell practicality and cost. Practical, cost-effective designs can only be developed if adequate market demand is likely. The issue of market potential is discussed more fully in Sections 6 and 7.

3.0 COMPETING TECHNOLOGIES

3.1 Introduction

The versatility of fuel cells is such that they will compete across a wide power range and in a number of quite distinct application areas. New markets can be expected to develop, taking advantage of unique fuel cell characteristics. If this proves to be the case, it is most unlikely to start on a commercially significant scale. The importance of relatively small-scale applications (for example, those in the aerospace and military spheres) should not be underestimated. However, for the most part, fuel cells will be obliged to compete in established markets, such as power generation and transportation, already served by well-proven and deeply entrenched power sources. Furthermore, the fuel cell will not be the only new contender trying to break into these vital applications. Although fuel cells may well find themselves in competition with other new power sources, vying for scarce research, development and demonstration funds, the principal challenge will come from the established technologies. To put this into perspective, the level of R&D expenditure on established technologies is at least two orders of magnitude greater than the best that can be expected for fuel cells over the next decade. Much of the R&D is being committed to areas where fuel cells are seen as holding the high ground (e.g., efficiency and emissions). As a consequence of this, fuel cells will have to achieve ever-higher performance levels, if they are to establish a clear advantage over rival technologies.

As with other developing technologies, there are several different responses to this type of problem. For example, some will put emphasis on developing new fuel cells, with much improved characteristics but requiring substantial R&D investment over a significant additional period before deployment. Another approach is to concentrate on applications which are particularly well suited to the performance parameters of the available products. These are not necessarily the largest markets, but serve to establish a commercial beachhead, which can be expanded as more capable products become available. A third approach is to advocate special consideration which will give the developing technology favorable treatment. The latter may include financial assistance with early commercial installations, where many countries offer some form of subsidy to help bring new technologies to the marketplace. These are generally on quite a small scale, but some involve fundamental rule changes that can have a more dramatic impact (e.g., steps taken to overcome air quality problems in California by encouraging the introduction of wind power in the 1980s and electric vehicles in the late 1990s).

For the power generation and marine industries, the main competition in the sub-1MW range comes from reciprocating engines. Limited progress is being made in improving the efficiency and emissions of reciprocating engines, but they are unlikely to reach the levels attainable by fuel cells. In sensitive areas, this already compensates for the relatively high cost of fuel cell systems.

At multi-MW power levels and in the military marine industry, gas turbines account for a larger part of the market and a rather different situation applies. Gas turbine emissions are falling rapidly, with the development improved and more efficient combustion systems, particularly Intercooled Recuperative Systems. These can close roughly 90 percent of the gap between a typical utility's present performance and that promised by a fuel cell. There now

appears to be a real prospect of a further major advance through the introduction of catalytic combustion systems, which may result in emission levels on a par with those of fuel cells.

Gas turbine efficiency represents another area where progress is impressive. Large-scale combined cycle or advanced cycle systems are expected to provide top efficiencies on the order of 50 percent operating on natural gas or 40 percent in integrated coal gasification plants. Even at lower power levels (of a few MW or tens of MW say), use of modified turbine cycles is becoming more commonplace, offering efficiency levels comparable to those of first generation fuel cells (although below those of high temperature fuel cells).

Natural gas is increasing its share of the fuel market for thermal power generation at present, due to a mix of commercial and environmental factors. However, coal retains a very important position in new plants as well as in the installed base, which will increase further as gas resources diminish. Most of the pollutants associated with power generation are attributable to coal. Future advanced coal plant designs, whether steam turbine based or with a substantial gas turbine component, will typically reduce pollutant emissions by more than 90 percent (compared to uncontrolled plant emissions), while yielding efficiencies in the region of 45 percent-50 percent at the highest power levels.

Given the scale of the competition, fuel cells will need to mount a strong challenge to capture a significant share of the potential power source market.

3.2 Marine Diesel Engines

Diesel engines operate on either a two-stroke or four-stroke cycle of events in each cylinder, and are commonly referred to as 2-cycle or 4-cyle engines. That is, the engine requires ether two or four piston strokes to draw in a charge of air, compress it to a high pressure and temperature, inject and burn the fuel, allow the exhaust gases to expand and deliver power to the crankshaft, and blow out exhaust gases so that the cylinder is ready for the next cycle. The two strokes of a 2-cycle engine require one revolution of the crankshaft while the 4-cycle engine requires two revolutions of the crankshaft.

In addition to being categorized by stroke cycle, diesel engines are also categorized by speed and are normally referred to as low, medium and high speed engines. There is really no established limit for each class, nor is there agreement in the industry whether piston speed or engine rotational speed is used for categorization. Consequently, these terms are for the most part relative.

Low speed diesel engines are the predominant propulsion prime mover in large chemical carriers, container ships and tankers due to their efficiency, simplicity and inherent reliability. These engines are typically 2-cycle, turbocharged, crosshead piston type engines operating at rotational speed of 250 rpm or less and are available in ratings from 2 MW up to approximately 68 MW. However, most low speed diesel engines operate below 100 rpm. This permits the engine to drive the propulsor directly, thereby eliminating the need for a reduction gear and associated drive train losses. In addition, low speed diesel engines generally burn cheaper, low grade, residual or heavy fuels of up to 700 cSt viscosity (maximum specific gravity of 1.010) using appropriate fuel treatment systems. However, during starting and maneuvering

operations and prior to extended shutdown of the engine, marine diesel oil (MDO) is used in lieu of heavy fuel to minimize fouling in cylinders.

The advantages of low speed marine diesels, as cited by a major marine diesel manufacturer, include:

- Greater than 90% availability,
- Greater than 98% load factor,
- Less than 1.5% forced outage rate, and a
- Robust dependable design capable of running on any commercially available liquid or gaseous fuel.

For fuel cells to be competitive with a product line offered by typical marine diesel manufacturer, similar availability, load factor, and forced outage rates will have to be provided to the marketplace. If these levels of operating specifications can be met, there may be significant market potential for price competitive fuel cells.

A disadvantage of low speed diesels is their relatively large volume and weight, with a power density of 1.9 ft^3/kW and specific weight of 75.6 lb/kW typical for propulsion engines in the 14 MW range. The vendor cost of low speed diesel engines generally range from \$270/kW to \$400/kW depending on options specified, cylinder bore and rpm. This cost range does not include installation cost, nor operating and support costs.

Medium speed diesel engines are used as propulsion prime movers in smaller vessels and work boats, ferries and other applications where the space and weight of a low speed diesel engine would be prohibitive, as well as for electric power generation. In marine applications, these engines may be 2-cycle or 4-cycle, and are turbocharged, trunk piston type engines operating at rotational speeds between 400 and 1,000 rpm. At these higher rotational speeds, a reduction gear is typically provided to reduce the engine rpm to match the propulsor rpm. Medium speed diesel engines for marine propulsion are available in ratings up to 39 MW. For electric power generation, the engines drive generators directly at the synchronous speed of the generator, namely 514, 720 or 900 rpm for 60 Hz systems. Similar to low speed diesel engines, many commercial marine medium speed diesel engines generally burn cheaper, low grade, residual or heavy fuels of up to 700 cSt viscosity (maximum specific gravity of 1.010) using appropriate fuel treatment systems. MDO, distillate, or gas oil, depending on the manufacturer's recommendations, must also be used during starting and maneuvering operations, light engine loading conditions, and prior to extended shutdown of the engine in lieu of heavy fuel.

A power density of 0.7 ft^3/kW and specific weight of 33.7 lb/kW is typical for medium speed propulsion diesel engines in the14 MW range. For smaller medium speed propulsion engines in the 1.5 MW range and operating at the upper end of the rpm range, the above power density and specific weight is typically 0.4 ft^3/kW and 23.2 lb/kW, respectively. For ship service generator sets in the 2.5 MWe range and operating at the upper end of the rpm range, the power density and specific weight are approximately 0.85 ft^3/kW and 27.6 lb/kW, respectively. The vendor cost of medium speed propulsion diesel engines can vary significantly depending on the rpm of the prime mover. For medium speed ship service diesel generator sets

of 2.5 MWe capacity as described above, $400/kWe is commonly used for estimating purposes. This cost does not include installation, nor operating and support costs.

High speed diesel engines are used as propulsion prime movers in smaller vessels and work boats, fishing boats, pleasure boats, high performance crafts, as well as for electric power generation. In marine applications, these engines may also be 2-cycle or 4-cycle, and are turbocharged, trunk piston type engines operating at rotational speeds above 1,000 rpm. At these higher rotational speeds, a reduction gear is required to reduce the engine rpm to match the propulsor rpm. High speed diesel engines for marine propulsion are available in ratings from approximately 100 kW to 8.1 MW. For electric power generation, the engines drive generators directly at the synchronous speed of the generator, typically 1,200 or 1,800 rpm for 60 Hz systems. Unlike, low and medium speed diesel engines, high speed diesel engines generally only burn more expensive diesel fuel or gas oil.

A power density of 0.3 ft^3/kW and specific weight of 11.2 lb/kW is typical with high speed propulsion diesel engines rated at the upper end of the power range. For smaller high speed propulsion engines in the 500 kW range, the power density and specific weight typically range from 0.28 to 0.43 ft^3/kW and 16.6 to 21.9 lb/kW, respectively for engines operating at the upper and lower ends of the rpm range. For ship service generator sets in the 500 to 1,000 kWe range and operating at the lower end of the rpm range, the power density and specific weight are about 0.6 to 0.8 ft^3/kW and 27.0 to 33.2 lb/kW, respectively. As discussed previously, the vendor cost of high speed propulsion diesel engines can vary significantly depending on the rpm of the prime mover. For high speed ship service diesel generator sets of 500 to 1,000 kWe capacity, vendor costs can range from $110 to 260/kWe. This cost does not include installation, nor operating and support costs.

For the marine and power generation industries, diesel engines are the primary competition to fuel cells in the sub-1MW range. Progress has been reported in the operating characteristics of these reciprocating engines, but they are unlikely to seriously challenge the fuel cell's advantages in terms of efficiency goals, environmental performance and quiet operation. However, engine manufacturers have made numerous advances in recent years to improve reliability and reduce ownership costs. Some of these advances include:

- More sophisticated analytical and finite element techniques to assess component temperature and stress profiles allowing optimum use of materials with resulting reductions in weight and cost.
- Advanced materials that are lighter and more resistant to high temperatures and corrosion.
- Use of acoustic enclosures and compound or double resilient mounting systems in applications where stringent noise and vibration limits are invoked.
- Electronic governors and more comprehensive monitoring systems which more accurately and reliably control and monitor critical engine parameters.
- More sophisticated engine condition monitoring techniques including lube oil analysis, vibration measurement, on-line measurement of rpm, crank angle, cylinder pressures and fuel consumption, and trend analysis of key parameters for

purposes of maintaining optimum engine performance and performing maintenance based on the actual engine condition vice a predetermined schedule. It should be noted that maintenance schedules can vary significantly depending on the stroke cycle of the engine, rpm and type of fuel burned. As an example, commercial marine low speed and medium speed propulsion diesel engines typically undergo major overhauls at intervals between 12,000 and 20,000 hours depending on the type of fuel burned and load profile to which the engine has been subjected. For high speed diesels, the overhaul intervals vary widely depending upon the manufacturers' recommendations and can range as low as 6,000 hours to as high as 20,000 hours depending upon the rpm and load to which the engine has been subjected.

- Use of sequential turbocharging to permit wider engine operating envelopes, improved capability to operate at very low and high engine speeds, and lower smoke emissions, exhaust gas temperatures, and fuel consumption.

No significant improvements have been made in small diesel engine thermal efficiencies over the last two decades. For the purposes of this study, "small" is defined as <1 MW. Manufacturers' literature in the 1980 timeframe showed peak efficiencies of 33 percent. Current literature (Moore 1998) shows the same value. With water emulsified fuel modest improvements in specific fuel consumption may be achieved. A maximum of 3 percent increased efficiency can be expected with a combined cycle diesel installation ("Diesel Delivers Economies", 1999). Future improvements in diesel power plant efficiency are not expected to reach the levels anticipated for fuel cells. It is expected that selective catalytic reduction systems (or other forms of pollutant emission controls) will be required to reduce diesel exhaust emissions in the future, which may result in somewhat degraded overall efficiency. Since fuel cells are clearly superior for minimizing emissions, they are likely to maintain that advantage over diesels.

3.3 Marine Gas Turbines

Marine gas turbines generally are developed from either of two sources, namely land-based power units or aircraft engines. Land-based units tend to be very large and very heavy while aero-derivative turbines are smaller and lighter than the land-based units, but are less durable and rugged. Since weight and volume traditionally are important considerations in shipboard applications and since marine engines operate for much fewer hours and at lower power levels than do land-based units, most large marine gas turbine engines are of the aero-derivative type.

Marine gas turbines have power turbines that are either mechanically coupled or aerodynamically coupled to the gas generator section. Each configuration has its advantages and disadvantages. Mechanically-coupled engines allow power takeoff from the compressor and exhaust ends, however, the minimum power turbine rotational speed is fixed at a relatively high level because the same shaft also drives the low-pressure compressor stages, which cannot turn too slowly or the engine will stall. Aerodynamically-coupled engines can operate at very low power turbine speeds, since the power turbine is not directly coupled to the compressor.

Most marine gas turbines are simple cycle, having only compression, combustion, and expansion processes typical of a Brayton open cycle. The Northrop Grumman WR-21 engine currently under development has rating of about 19.7 MW. The WR-21, however, is not a simple cycle engine. It has an intercooler and recuperator (also called a regenerator), so it often is referred to as the ICR engine. The ICR cycle provides good fuel efficiency even at low power levels, but it does so at the expense of added complexity, size, and weight. Because of its intercooler and regenerator, the ICR engine fuel consumption is less than those of the other engines, but its weight-to-power ratio is about 5.2 lb/kW. However if endurance fuel load is included in the power-to-weight ratio, the ICR engine becomes more attractive and merits further consideration. The WR-21 gas turbine is currently undergoing full system tests and is expected to undergo a 3,000 hour qualification test in mid-2000.

Recent trends in marine gas turbine development are towards higher ratings for shipboard application which are driven primarily by the naval market. The following are some of the potential gas turbines which are currently available or may be available in the future for use in the high power market:

- **General Electric LM2500+.** An upgrade of the LM2500 aero-derivative engine, the LM2500+ is a simple cycle gas turbine engine with an ISO continuous rating of about 27 MW and a U.S. Navy rating of 26.1 MW. Initially derived from the TF-39 engine developed for the C5A aircraft program and also on DC-10 wide-bodied jets, the LM 2500+ is a two-shaft design with an output speed of 3600 rpm that permits direct coupling to a 60 Hz generator.
- **General Electric LM6000.** This engine is not in service as a marine propulsion engine, however, it is derived from the GE CF6-80C2 jet aircraft engine used in the Boeing 747 and 767, the McDonnell Douglas MD-11, and the Airbus A300. The engine may be designed for simple-cycle, combined-cycle and cogeneration installations, has an output speed of 3600 rpm and can be directly coupled to an electric generator for 60 Hz applications. The LM6000 has an ISO rating of about 43.9 MW and an estimated U.S. Navy continuous rating of 37.3 MW. Over 160 LM6000 units are currently in shore-side operation for simple-cycle, combined-cycle or cogeneration projects.
- **General Electric LM6000 Sprint I.** This engine is an upgrade of the LM6000 which utilizes a SPRay INTercooling (SPRINT) design that injects water spray through nozzles between the high-pressure and low-pressure compressors. The water is atomized before injection using gas turbine high-pressure bleed air. This method of combustion air intercooling boosts power output over the baseline LM6000 by approximately 9 percent at ISO ambient temperatures and approximately 20 percent at 90 degrees F.
- **Rolls Royce Marine Trent.** The Marine Trent is based on the on the Rolls-Royce Industrial Trent power generation gas turbine which, in turn, is a derivative of the Trent 700 and 800 aero engines. The engine has a marine rating of approximately 47.5 MW. The three-shaft design Marine Trent engine replaces the industrial dual gas/liquid fueled combustion system with a simplified liquid only system.

The above candidates for naval and marine high power applications all have much lower weight-to-power ratios than comparable industrial units. The specific weight of industrial units range from about 4.5 to 6.7 lb/kW, while the specific weight of aero-derivative turbines range from about 1.2 to 1.9 lb/kW. The specific volume of the above aero-derivative turbines range from 0.09 to 0.13 ft^3/kW. These numbers are for comparison purposes only and differences within a group might be greater or less than they appear because of the way each manufacturer calculates engine weight and volume.

While trends toward higher propulsion power levels are being driven by future naval applications, many military and commercial vessels requiring the low specific weight of gas turbines have and continue to employ propulsion gas turbines at the lower end of the propulsion power range from 10.6 to 22.0 MW.

In addition to propulsion applications, marine gas turbines with ratings of 2.5 MWe have been used primarily by the Navy for ship service power generation. However, the use of marine gas turbine generator sets below 2.5 MWe is limited due to competition offered by diesel engine manufacturers in this lower power range. Moreover, as many gas turbines in this lower power range operate at relatively high rpm, a reduction gear is typically required to match the power turbine rpm to the generator rpm resulting in some loss in its primary advantages with regard to specific weight and volume. With current U.S. Navy and cruise ship trends toward high power integrated electric drive systems, there will be increasing applications for marine gas turbine generators in the 10 to 25 MWe power range.

With improved combustion techniques, gas turbine emissions are expected to decrease significantly. However, the acknowledged gap in thermal efficiency of simple gas turbines relative to fuel cells (shown in Figure 4) will not be closed in the foreseeable future. Thermal efficiency, coupled with even lower efficiency of the simple gas turbine (relative to fuel cells) at loads less than 50 percent -- where many ships spend a large portion of their operating lives -- make fuel cells attractive. A comparison of simple gas turbine technology characteristics in 1980 and 1998 shows that very little, if any, improvement has occurred in specific fuel consumption. Therefore little, if any, improvement in fuel economy is envisioned for simple turbines. However, greater efficiencies may be achieved with the incorporation of additional complexities such as combined cycle or other advanced systems. Because of the disadvantages of simple gas turbines compared to either diesel or fuel cells, turbines are not expected to emerge as a large-scale competitive threat in most marine applications.

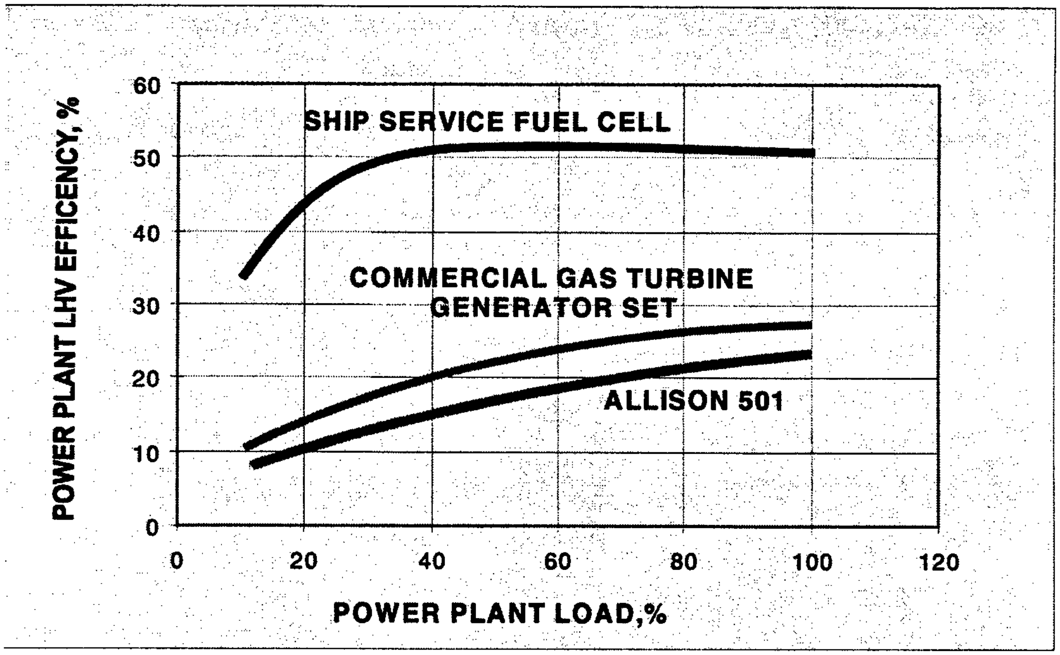


Figure 4. SSFC Efficiency Compared To A Gas Turbine
Source: Gaezel-Ayagh, H., ERC Inc., July 1999.

4.0 MARKET DRIVERS FOR ALTERNATIVE MARINE POWER TECHNOLOGIES

4.1 Factors to Consider When Assessing Fuel Cells vs. Competing Technology

Table 3 summarizes a number of key criteria upon which the choice of preferred power technology will be based in the future. These criteria represent characteristics of MCFC and PEMFC candidates. The table compares those characteristics with diesel and gas turbine technologies, the two prime competing propulsion candidates. Criteria can be categorized into three basic types: 1) technological, 2) application specific and 3) cost, as described below. While the criteria summarized in Table 3 are critical to the overall success of MCFC and PEMFC in comparison with alternative technologies, the actual values presented in Table 3 should be considered working numbers. As the technologies mature and experience is gained, specific values may change; however, the key criteria will remain important.

4.1.1 Technological Criteria

Technological criteria include thermodynamic efficiency, load share flexibility, distributed power potential, noise and vibration, emissions, fuel quality and start-up characteristics. One key advantage of both MCFC and PEM over diesel and gas turbine combustion cycle engines is the relatively flat thermodynamic efficiency curve of each fuel cell technology as a function of percent load. This advantage is important in applications where percent load variation is high, or where the same engine operates in low load regimes for extended periods with high percent load regime availability required on demand. A second thermal efficiency advantage of fuel cells is the higher optimum goal efficiencies attainable, as shown in Table 3.

Flexibility in load sharing is also an inherent advantage for both MCFC and PEMFC fuel cells for two reasons. First, fuel cell installations can be modular, providing some flexibility to the designer. Second, discrete units do not have to be brought on-line sequentially to match prevailing load conditions, as would be the case with combustion engines. However, modern programmable control systems based on digital technology can optimize the addition and deletion of combustion units, which mitigates somewhat the load sharing advantages of fuel cells.

A third technological advantage of fuel cells is the inherent applicability of the technology to distributed power applications. Because internal combustion engines are discrete, they can distribute power through the use of generators that are driven mechanically. In this sense, electrical power is slaved to engine power, whether the engine is functioning as a ship propulsion source or a ship set generator, and ancillary power must be managed through a separate power management system. In contrast, fuel cell output can be moderated for primary use, while cycling or peaking power applications can be supported in parallel, assuming that the fuel cell array is sized to accommodate the total load. Fuel cell sizing to demand is relatively easy because the technology is inherently modular.

A fourth technological advantage of fuel cells is low levels of noise and vibration. Sources of noise noted in Table 3 are due solely to ancillary sources in balance of

plant. Advantages or disadvantages due to thermal signature are not necessarily clear cut. In the case of MCFC, infrared (IR) signature may be a consideration for certain applications. Heat rejection and resulting temperatures may be high and may approach 1200° F.

Technological disadvantages inherent to fuel cells are also shown in Table 3 For example, quality of fuel, tolerance to sulfur content in the fuel and start-up characteristics inherently favor diesel and gas turbine engines. Complexity associated with reformer technology will be reflected in balance-of-plant design complexity, and therefore overall system cost as described below.

4.1.2 Application Specific Criteria

Application specific criteria include: safety considerations, response to load change, power density, specific weight, competitive power range and load following ability as shown in Table 3. These are referred to as application criteria because technology choice is likely to depend on the specific use or application that is being considered. For example, MCFC operates at inherently high temperature. PEM operates at inherently high pressure. Advantages or disadvantages of each will depend on the ship service, and the design specifications that are appropriate for the service. Another example of application specific choice is specific weight. In applications where optimized design requires minimum weight, perhaps a gas turbine is the engine of choice because that option has the lowest specific weight as shown in Table 3. For most applications, specific weight may not be a major consideration; the higher specific weight of MCFC and PEM technologies may actually provide an advantage in terms of overall ship mass properties.

4.1.3 Cost

Cost advantage and disadvantage criteria comprise capital cost, maintenance cost and operating costs. These concepts can also be expressed life cycle, current period or present value bases. Table 3 summarizes some of the key cost categories for propulsion and ship set generator options. However, a number of considerations are important in the use of cost comparisons. First, it is very difficult to summarize factored costs for propulsion systems and ship set generator systems. Costs can vary widely due to application specific considerations. Design criteria can also have a large affect on capital costs and maintenance costs.

Second, capital cost, operating costs and maintenance costs that are derived from the literature are difficult to compare. Some capital and operating cost numbers are for the power plant itself, absent installation costs, ancillary system costs, balance of system costs or costs associated with the ship infrastructure. Other capital cost numbers available in the literature are associated with units of widely different power ratings. Economies of scale reflected in these very different types and sizes of power plants make comparison of capital costs in terms of dollars per kilowatt difficult.

Third, capital cost, operating costs and maintenance costs associated with production versions of both MCFC and PEM technologies are difficult to catalogue because these technologies are not yet available in production configurations. In addition, the cost and complexity of both fuel cell technologies will be affected strongly by balance-of-plant designs.

As fuel quality degrades, reformer technology complexity and cost will increase. Fuel treatment complexity is likely to increase both capital cost of the overall system and maintenance costs.

Some of the data from industry sources included in Table 3 represent the best judgements of experts in the fuel cell industry at this time. Table 3 contains notes where these data reflect performance goals and design expectations. While the goals of experts are considered valuable, regular monitoring of costs may be appropriate on an ongoing basis.

Table 3. Comparison of Market Drivers for Alternative Marine Power Technologies

CRITERION	MCFC	PEM	DIESEL	GAS TURBINE	REFERENCE
Safety considerations	High temp, 1200°F, low pressure flow (1 atm) operation. Insulation required	High pressure flow (6 atm) low temp, 80°C operation. Insulation required	Thermal insulation required for exhaust and other hot surfaces.	Thermal insulation required for exhaust and other hot surfaces.	ABS 4/9.61.5 ASTM F683
Efficiency over a wide range of loads	Relatively flat[1]	Relatively Flat[2]	Best at > 75%, poor at partial load	Best at > 80%, very poor at partial load	
Flexibility to load sharing	All units on line at reduced power	All units on line at reduced power	Discrete units added/deleted	Discrete units added/deleted	
Response to load changes	Slow at start-up fuel/reformer dominated	Fuel/reformer dominated	Good	Fast	
Thermal efficiency. • Peak • Half • Low	40-55%[3] 50-52% (LHV)[13]	39-42[4]	33-36%[5] 33% 29% 23% Note: Low speed diesel may reach 40% efficiency.	26-30%[6]	For approx. 1 MW, manufacturer's literature, ca 1980
Power density (ft^3/kW)	2.0 – 1.0, 50% packing factor[3] (power plant)	0.30 – 0.20, 50% packing factor[3]	0.86[3] 1.9 - Low speed propulsion engine (14MW range)[15] 0.7 - Med speed propulsion engine (14 MW range)[15] 0.3 - High speed propulsion engine (8MW range)[15] 0.85 - Med speed SSG (2.5 MWe range)[15] 0.6-0.8 – High speed SSG (0.5 MWe – 1.0MWe range)[15]	0.94[3] 0.9-0.13 (High power propulsion gas turbine)[15] 0.11-0.13 (10.6-22 MW Propulsion gas turbine)[15] 0.8 (1 MW SSG)[15]	

Table 3. Comparison of Market Drivers for Alternative Marine Power Technologies (Cont.)

CRITERION	MCFC	PEM	DIESEL	GAS TURBINE	REFERENCE
Specific weight (lb/kW)	60 - 40[3]	12 - 6[3]	31-36, near/far term, also[7] 75.6 – Low speed propulsion engine (14 MW range)[15] 33.7 – Medium speed propulsion engine (14 MW range)[15] 11.2 – High speed propulsion engine (14 MW range)[15] 27.6 – Med speed SSG (2.5 MWe range)[15] 27.0-33.2 – High speed SSG (0.5 Mwe-1.0 MWe)[15]	27[3] 1.2-1.9 (High power propulsion gas turbine)[15] 2.0-3.1 (10.6-22 MW propulsion gas turbine)[15] 2.0 (1 MW SSG)	
Distributed power potential: • Ships service	High	High	Medium	Low, limited units available	
Capital cost for SSG ($/kWe)	$570/kWe-$1,500/kWe current estimate[8]	Current estimates (Goals)[9] $900-$1200/kWe (>2.5 MWe) $1500-1800/kWe (>200 kWe)	$400/kWe for 2500 kWe[15] $110-260/kWe (0.5-1.0MWe)[15]	$425-480/MWe (up to 10 MWe range)[15]	
Maintenance cost, ($/operating hour) • Propulsion engine • Generator set (0.5-6.5 MWe range)	$7/hr[13]	Not Available	$9-18/Hr.[15] $7-12/Hr.[15]	30% greater than diesel[10]	
Operating fuel cost ($/operating hour) • Generator set	Fuel cost and FC Efficiency driven $0.03/kWe-hr[17]	Fuel cost and FC efficiency driven[14]	$0.049/kWe-hr[16]	$0.056/kWe-hr[16]	
Maintenance intervals	6 months[13]	Not Available	12,000-20,000 hours (low and med speed diesel engines)[15] 6,000-20,000 (High speed diesel engines)[15]		
Life	5 years (goal)	5 years (goal)[14]	20+ years	20+ years	
Generated noise, vibration	Low, unit in enclosure for heat, noise	Low unit in enclosure for noise	High - Resilient or compound resilient mounting may be required to minimize structure borne noise	Medium – Resilient or compound resilient mounting may be required to minimize structure borne noise	IMO Res. A.468(XII) SNAME T&R Bulletin 2-25

Table 3. Comparison of Market Drivers for Alternative Marine Power Technologies (Cont.)

CRITERION	MCFC	PEM	DIESEL	GAS TURBINE	REFERENCE
Specific fuel consumption, (SFC) lb/kW-hr.	0.37-0.35 (30-100% load)[13]	0.46-0.32	0.39*-0.35**	0.44*-0.35**	Marine Technology.
NO_x, CO, HC emissions CO2	Very low, reduced CO_2	Very low, reduced CO_2	Medium, reduced NOx with emulsified fuel, no CO_2 benefit[12]	Medium, no CO_2 benefit	
Competitive power range	Emerging, 500kW to 2500 kW, modular 0.25-3 MW[13]	Emerging, 20kW to 2500kW, modular	Up to 68MW	Up to 50 MW	
Quality of fuel required (Logistics fuels)	Very high, unavailable w/o desulfurization. Reforming required	Very high, unavailable w/o desulfurization. Reforming required	Low is acceptable. (available)	High, reduced sulfur required (available)	
Tolerance to sulfur in fuel	Very low levels required	Very low levels required	Insensitive	Limited	
Start-up and warm-up characteristics	Hours	Less than MCFC	Minutes	Seconds	
Load following ability • Propulsion • Service power	 Good (2003 est.) Fair	 Good (2003 est.) Fair	 Very good Good	 Excellent Very good	

[1] Steinfeld, et al.
[2] Ibid.
[3] Allen, et al., 1998
[4] Ibid.
[5] Moore 1998
[6] Ibid.
[7] "Propulsion Machinery Working Group Summary", 1998
[8] Goubalt, et al., 1994 and Allen, et al., 1998
[9] Runte, 1998.
[10] "Diesel Delivers Economies", 1999
[11] Ibid.
[12] Ibid.
[13] Abens, Sandy, ERC, personal communication on April 15,1998.
[14] Tharp, M., MTI, personal communication, March 1999.
[15] John J. McMullen, Associates, data derived from various ship design projects.
[16] Operating fuel cost based on near-term specific fuel consumption listed in Table 3 and $36.96 per barrel.
[17] ERC Inc., estimates of operating fuel costs, July 1999..

Notes:
* near-term (Peak Efficiency)
** far-term (Peak Efficiency)

4.2 Market Challenges To Marine Applications Of Fuel Cells

Fuel cells will be competing in large established markets with the conventional technologies of diesel engines and gas turbines. Fuel cells have acknowledged superiority in efficiency and reduced emissions, and are expected to retain this advantage even though R&D related to the rival technologies is focused in those areas. The market challenges to fuel cells exist where diesel and turbines are strong: their superiority relative to a broad infrastructure, operating characteristics, demonstrated life and maintenance schedules. Table 3 outlines these factors.

4.2.1 Relative Strengths

The MCFC and PEMFC systems are considered to have the following favorable characteristics when compared to corresponding applications of marine diesel engines and gas turbines, (Goubault, et al. 1994 and Allen, et al. 1998):

- Increased thermal efficiencies over the entire operating range (with resultant fuel savings and costs). This is especially significant at the low load levels where diesels and gas turbine efficiencies drop off. The fuel cell efficiencies are also greater over the entire spectrum of power plant load. (See Figure 5)
- Anticipated operating simplicity and reduced manning requirements.
- Incorporation into an all-electric ship with an integrated power system and zonal distribution.
- Inherently quiet operation and low heat rejection rate.
- Significant reduction of CO, NO_x and HC emissions and lowering of green house gases (CO_2).

4.2.2 Implementation Issues

Implementation issues may be segregated into competitive issues and relative fuel cell technology issues. The competition to fuel cells provided by internal combustion engines and the maturity of the molten carbonate and the proton exchange membrane fuel cells are discussed in the following paragraphs.

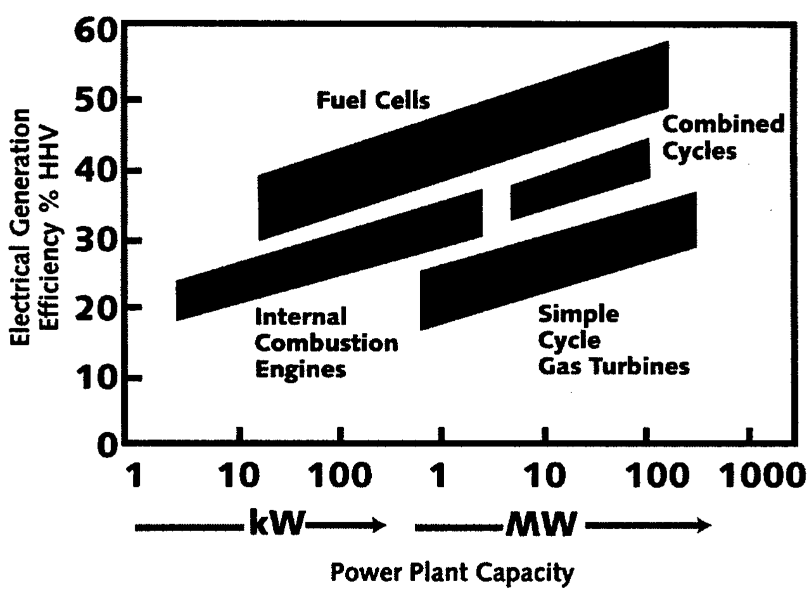


Figure 5. Performance Comparison

Source: Allen, Ashey, Gore, Woerner and Cervi, "Marine Application of Fuel Cells" *Naval Engineers Journal*, January 1998.

4.2.2.1 Fuel Considerations

A major barrier to the consideration of fuel cells for marine application is that virtually all vessels use diesel fuel, and the logistics infrastructure is well developed world-wide. Fuel cell development and availability has concentrated on the processing (reforming) of natural gas and methanol to produce the hydrogen required for fuel cell operation. The use of logistic fuels; medium distillate hydrocarbon fuels such as DF-2 and NATO F-76 require a more complex reforming process and the complexity increases as the heavier distillates are considered. In addition, sulfur present in diesel fuel poisons the catalyst used in the reforming process and the fuel cell stack. Even JP-8 which has an 0.3 percent (max) sulfur allowable requires desulfurization before reforming. Therefore low sulfur fuel (goal 100ppb) must be available, or desulfurization must be performed aboard ship for fuel cell use. The front-end complexity and cost of the reforming and desulfurization process for logistics fuels must be borne by the fuel cell when competing with internal combustion devices. The use of natural gas (CNG or LNG) if consistently available for vessels would simplify considerably the implementation of fuel cells for marine use. Work on reformer development and weight and volume estimates for auto thermal reformers (ATRs) and steam reformers, and desulfurizers for a 2500 kW unit are provided in Allen, et al. 1998 (see Figure 6). Progress in reformer effectiveness may be a critical factor in establishing fuel cells as viable competitors to internal combustion technology.

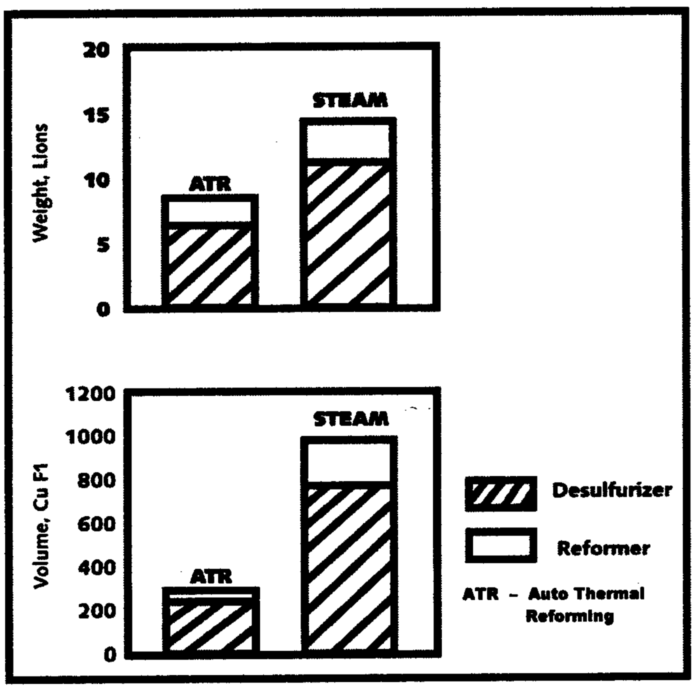


Figure 6. 2500 kW Fuel Processor Comparison

Source: Allen, Ashey, Gore, Woerner and Cervi, "Marine Application of Fuel Cells" *Naval Engineers Journal*, January 1998.

4.2.2.2 Fuel Cells (MCFC and PEMFC)

As shown in Table 4, a number of developmental issues pertaining to both the MCFC and PEMFC need to be resolved. With successful resolution of these issues, fuel

cell plant sizes are expected to be in the multi-MW size in the 2010 time frame (Goubault, et al. 1994). A comparison of the issues and advantages for these two fuel cell types is shown in Table 4. At this time it is premature to predict which issues and advantages will emerge as dominant in commercial deployments. However, it appears that the development risks associated with either technology are moderate (Allen, et al. 1998).

Table 4. Comparing MCFC and PEM Fuel Cell Issues and Advantages

	FUEL CELL TECHNOLOGY	
	MCFC	**PEMFC**
Issues	Low kw/ft^3 Long start up time Seals Halide control CO_2 balance	Water balance Membrane life CO intolerance
Advantages	CO tolerant High efficiency Direct reforming of some fuels	High kW/ft^3 Short start time No corrosive liquids Differential pressure tolerant

5.0 MARKET ANALYSIS

This section outlines the overall methods that were used to develop the results shown in Section 6 of this report. The sources of data and information, analytical methodology and basic premises are described. Particularly important are the rationales related to the use of historical data. For some purposes, 38 years worth of data were used. For other purposes, very recent data were used because they represent a more accurate reflection of likely technology use in the future. Perhaps the most important example of the use of recent data is the consideration of only those vessels built in the 1990's to project the types and sizes of propulsion and SSG units that are likely to be deployed over the period of this study. The analysis follows the following main steps:

1) Identification of Sources and Data Collection
2) Grouping of Market Segments
3) Application of an Analytical Methodology

5.1 Sources – Market Data Collection

5.1.1 Sources Of Vessel Data, World And U. S.

Marine power market segments can be segregated by general application, so this study analyzes worldwide commercial markets based on ship application type. Commercial vessel information for ships greater than 100 gross tons was provided by Lloyds Marine Information Services (LMIS). Information on the U.S. military and commercial shipbuilding market was gained from maritime trade journals such as Maritime Reporter, Motor Ship, and Marine Log. From LMIS, a database was developed that contains key information on a large fraction of the world's commercial fleet. A very large sample of the world commercial vessel population was chosen so that study results would not be dependent on country specific, application specific or regulatory-jurisdiction specific conditions.

5.1.2 Sources of Fuel Cell Data

Marine fuel cell sources of information included recently published papers in the open literature, interviews and various databases. Sources also included FC manufacturers (ERC, MTI) and ship design agents as well as recent papers in the Naval Engineers Journal, a Webb Institute thesis, and the 1998 Fuel Cell Seminar held in Palm Springs, CA, November 16-19, 1998. In addition to the above, the status of reformer technology was obtained from the Proceedings of the Fuel Cell Reformer Conference, November 20, 1998.

5.1.3 Sources of Diesel Engine, Gas Turbine Data

Characteristics of marine diesel engines and gas turbine propulsion came from a variety of sources including marine journal papers, JJMA, diesel manufacturers, the U.S. Coast Guard, and LMIS.

5.1.4 Sources of Comparative Market Penetration Rate

Market penetration rate forecasts are based on growth rates of the marine markets identified in this study. They are projections of the end-use marine applications for propulsion and ship service generator power plants. Comparative displacement by fuel cells of traditional power plants was forecast based on analysis of a number of other studies, and their projected penetration rates for fuel cell technologies. These penetration rates are based on land applications.

5.1.5 Interviews To Identify and Rank Factors That Are Market Drivers

The method used for this study adopted two separate survey techniques. Analysis of the Lloyds database was complemented by structured interviews. Candidates for these interviews included: a) design agents, b) shipyards, and c) ship owners/operators. The purpose of these interviews was to assess the level of interest in fuel cell technology by these important stakeholders and to learn from them what criteria are important in selecting power systems for marine applications.

5.2 Market Segments

In this subsection, major segments of the commercial market are identified. Ships in each of the major market segment categories share common operating characteristics and similar propulsion and ship service generator requirements. Ships in each market segment also tend to compete, so that penetration of each segment by early adopters is likely to force others in the segment to consider adoption of new technology.

5.2.1 U.S. Military Vessels Compared To World Fleet

U.S. military vessels represent only a small percentage of the worldwide fleet of ships. Figure 7 illustrates that the U.S. Navy, by itself, is unlikely to provide sufficient new ship construction to warrant development of new power technologies. The current world fleet of ships is larger than 87,000 vessels. By comparison, the U.S. military comprises a few hundred major ships. Therefore, this study has focused on the potential demand by global commercial markets.

5.2.2 International Commercial Vessel Market Segments

The market segments investigated in this study are the major subsets of the world commercial fleet. The vessel types comprising market segments in this study are shown in Figure 8. Major subsets are segregated by application type, such as fishing vessels, oil tankers, general cargo vessels, etc. because these applications tend to adopt similar propulsion and auxiliary power solutions. The segments chosen for the study capture 93 percent of the total world commercial market, and are analyzed in detail in this report.

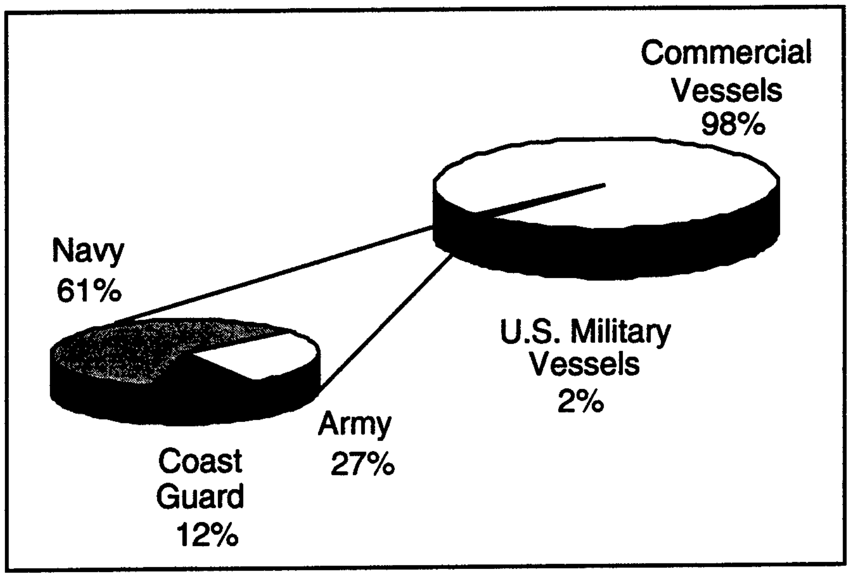


Figure 7. World Commercial Fleet Compared To U.S. Military Vessels

Bulk Carrier
Bulk Carrier
Bulk/Oil Carrier
Cement Carrier
Ore Carrier
Self-Discharging Bulk Carrier
Heavy Load Carrier
Wood Chips Carrier

Oil Tankers
Crude Oil Tanker
Oil Products Tanker

Other Tankers
Chemical Tanker
Chemical/Oil Products Tanker
Vegetable Oil Tanker
Water Tanker

Container Ships
Container Ship

Fishing Vessels
Live-Fish Carrier
Fish Carrier
Fishing Support Vessel
Fishing Vessel
Trawler

General Cargo Ships
General Cargo Ship
Deck Cargo Ship

Hoppers/Dredgers
Hopper Dredger
Dredger
Motor Hopper

LPG/LNG Tankers
LNG Tanker
LPG Tanker

Offshore Vessels
Offshore Processing Ship
Offshore Supply Ship
Offshore Support Vessel
Offshore Tug/Supply Ship

Passenger Vessels
Passenger (Cruise) Ship
Passenger Ship
Passenger/General Cargo Ship
Passenger/Ro-Ro Cargo Ship

Refrigerated Cargo Ships
Refrigerated Cargo Ship

Ro-Ro/Vehicle Vessels
Ro-Ro Cargo Ship
Vehicles Carrier

Tugs
Tug
Pusher Tug

Yachts
Yacht

Figure 8. Vessel Types Included In Each Vessel Category

5.3 Market Penetration — Analytical Methodology

This section outlines the methods used to forecast the numbers of vessels that will be built through the year 2015. It also outlines the method used for calculating the demand per vessel for propulsion units and for SSG units. Finally, this section develops the mathematical procedure for estimating the numbers of fuel cell power units that are forecast, both for propulsion and for SSG applications.

5.3.1 Fuel Cell Market Forecast Methodology

Projecting a realistic market potential for fuel cells was accomplished through a six-step process as follows and which is summarized in the following paragraphs.

- Step 1 - Existing Commercial Vessel Database
- Step 2 - Historical Market Trends
- Step 3 - January 1999 Vessels On-Order, Trend Validation
- Step 4 - Power Plant Rating, Current Trend
- Step 5 - Market Segments Projection By Vessel Type
- Step 6 - Forecast Rate Of Market Penetration.

5.3.1.1 Step 1 - Existing Commercial Vessel Database

The first step in the methodology was to construct a large database using existing commercial vessels information obtained from LMIS, the most reliable source that could be identified. The LMIS database yielded detailed information on approximately 87,000 non-military vessels of greater than 100 gross tons, which comprise a large percentage of the world's commercial fleet. The LMIS data suggest strongly that dominant commercial vessel power applications define major market segments based on ship type.

5.3.1.2 Step 2 - Historical Market Trends

The second step was to develop historical trends in major market segments starting in the year 1960. These trends were analyzed and ranked by size (i.e., number of vessels) to assess market segment stability. For the purposes of this study, stability is defined in terms of change over time in number of vessels built. This analysis identified those major market segments that have remained stable, those that have experienced growth and those that have experienced a decline over several decades. Based on historical trends, an assessment could be made of which market segments appear to be good candidates for reasonable forecast from the year 2000 through the year 2015. By breaking vessels into major application categories, trends in each category can be projected separately, and possible errors in projections of market segment vessel builds are limited to that market segment. By segregating the overall market into thirteen major segments, forecast errors among the individual market categories are expected to cancel to some degree.

5.3.1.3 Step 3 - January 1999 Vessels On-Order, Trend Validation

The third step in the process was to identify vessels on order in January, 1999. These vessels were analyzed and categorized by application. The number of vessels on order were compared with historically dominant market segments to yield a "latest look" into historical markets and trends. Vessels on order that reinforced historical trends increased our confidence that projected growth rates were reasonable. Analysis of vessels on order confirmed that no new market segments are emerging and that historically strong market segments currently account for most new construction.

5.3.1.4 Step 4 - Power Plant Rating, Current Trend

The fourth step in the process was to examine those vessels, again by major market segment based on application, built between 1990 and 1999. Historical vessel counts can be used to project with confidence those major market segments that are likely to be significant users of primary power (propulsion) and auxiliary power in the form of ship service generators (SSG). But power use by obsolescent vessels cannot be used to forecast ship power requirements. Ships constructed in the future may not reflect the same power requirements in terms of rating, numbers of units, or even motive power (e.g. steam vs. diesel) as vessels constructed several decades earlier. These newer vessel types were analyzed to identify power plants by kilowatt rating and number of propulsion and SSG units used. Within each population of several thousand ships that comprise each market segment, a "standard complement" of propulsion power and SSG power units was derived. The standard complement represents a norm, and varies for each market segment. Standard complements allowed data reduction to be performed as described in paragraph 5.3.2 and Appendix C. Standard complements of propulsion power and SSG power are thought to be accurate for each segment because they are derived using a large statistical sample of ships built in the 1990s, but these complements do not represent actual power plant numbers for any individual ship.

5.3.1.5 Step 5 - Market Segments Projection By Vessel Type

The fifth step in the forecast methodology process is to project the vessel forecast by market segment, and multiply the propulsion and SSG standard complement per ship, per market segment, based on the data for the 1990's. An important assumption underlying this last step is that vessel power requirements will not change significantly through the year 2015.

5.3.1.6 Step 6 - Forecast Rate Of Market Penetration

The final step in the forecast methodology was to project a market penetration rate based on maturation projections for fuel cell technologies. To project adoption rates, two assumptions were made. The first assumption is that because land based fuel cell applications are receiving more development funding than marine applications, early uses of fuel cells will be on land. The second assumption is that although marine applications will lag land applications, the lag will not be significant. The same technology and emission reduction advantages will apply to commercial deployment in both land and marine sectors. Land application penetration rates from a number of sources are shown in Section 7 of this report.

5.3.2 Propulsion and SSG Data Reduction

As stated earlier, two of the main objectives of the study are:

1) Characterize the number of power plants that will be required on commercial vessels through the year 2015, and
2) Forecast the probable sizes of units in terms of power output (kW or MW) that will be demanded by the marketplace.

To accomplish these objectives, data on propulsion and SSG power unit sizes were analyzed to develop reasonable forecasts for the numbers of propulsion and SSG units that would be required over the next 15 years. The method, described in this subsection, was used to reduce data to meaningful information for each market segment.

The power plant categories were divided into power ranges. The purpose of data reduction is to classify market demand for power plant size in terms of units that could be sold in high quantities and in power ranges that would be economically justifiable to produce. In other words, it would be desirable to identify one or a few standard output ratings (e.g. 250 or 500kW) where fuel cells could be produced and sold in large numbers.

Propulsion and SSG power plant data from the commercial vessel database were segregated by application category shown in Table 5. Offshore drilling rigs, which comprise a market segment of interest in this study, are not included in Table 5 and are discussed separately in paragraph 6.1.2 and Appendix C.

Table 5. Types of Vessels That Comprise Study Market Segments

SHIP TYPE	YEAR BUILT 1960-1969	1970-1979	1980-1989	1990-1998	Total	VESSELS ON ORDER January 1999
Fishing Vessels	4346	7906	7081	3283	22,616	236
General Cargo	2603	5431	4557	3098	15,689	474
Tugs	1408	2635	1856	1957	7,856	288
Oil Tankers	851	2420	1810	1623	6,704	338
Bulk Carrier	246	1848	2110	1654	5,858	292
Passenger Vessels	925	1383	1436	1427	5,171	187
Offshore Vessels	249	976	1149	247	2,621	70
Other Tankers	158	518	904	911	2,491	163
Container	32	421	587	1356	2,396	232
Hoppers/Dredgers	243	461	581	191	1,476	16
Refrigerated Cargo	161	400	537	313	1,411	33
RO-RO/Vehicle	69	516	531	280	1,396	119
LPG/LNG Tanker	82	300	302	377	1,061	70
Total	11,373	25,215	23,441	16,717	76,746	2,518

5.3.3 Methodology For Market Segments Potential Forecast

Following the identification of the major market segments, the method to establish vessel count trends was identified and discussed. Next the historical trends are discussed and shown to be consistent with current trends in vessels on order as of January 1999. Following the identification and validation of historical trends, the methodology that describes how the complement of SSG and propulsion units per vessel are identified is developed. With these methods, a simple calculation can be made to forecast the number of propulsion units of a certain power rating for each market segment. Similarly, the number of SSG units of a certain

power rating for each market segment can be calculated. The formula used to calculate the forecasted maximum number of propulsion units that could be required is shown in Equation 1. The formula used to calculate the forecasted maximum number of SSG units that would be required is shown in Equation 2.

$$\Pi_{k,i} = [\Sigma_{j,k} [S_{j,k} \times P_{j,k}]]_i \qquad \text{Equation (1)}$$

Where

$\Pi_{k,i}$ is the total number of propulsion power plants, adding across all 'j' market segments (there are 13 'j' market segments total), of size 'k' kilowatts forecast for each five-year block 'i' in the forecast period.

$S_{j,k}$ is the number of ships in 'j' market equipped with power plant of size 'k' kilowatts, in timeframe 'i', and

$P_{j,k}$ is the number of propulsion units of size 'k' kilowatts, that go into each vessel 'S' in market segment 'j'.

Similarly, the number of ship set generators forecast for year 'i' of size 'k' can be written:

$$\Gamma_{k,i} = [\Sigma_{j,k} [S_{j,k} \times SSG_{j,k}]]_i \qquad \text{Equation (2)}$$

where

$\Gamma_{k,i}$ is the total number of SSGs, adding across all 'j' market segments, of size 'k' kilowatts forecast for five-year timeframe 'i',

$S_{j,k}$ is the number of ships in 'j' market segment equipped with SSGs of size 'k' kilowatts, in timeframe 'i', and

$SSG_{j,k}$ is the number of ship service generators of size 'k' kilowatts, per vessel 'S' in market segment 'j'.

The methodology for the market analysis is expanded in more detail in Appendix C. The results of applying the methodology described in this section are shown in the market projections given in Section 7.

6.0 MARKET ANALYSIS – FINDINGS

The methodology described in Section 5.3 generated results in forecasts of power units that are tightly clustered by power rating for both propulsion and SSG uses. Because of the large volume of information presented as histograms for 13 major market segments, graphical presentations of key findings have been placed in Appendices C through H. The appendices represent core elements of study findings; they are not secondary or supplemental to this report.

Since the vessel counts, propulsion units and SSG unit forecasts are extrapolated for the world fleet, the resultant forecasts shown in this section reflect upper bounds of nominal forecast ranges for propulsion and SSG power for each size unit. The forecast process can project, with a degree of confidence, the sizes of units and the number of units required for propulsion and auxiliary uses from all sources of power (e.g., diesel, gas turbines, PEM, MCFC, etc.). The forecast does not project with confidence the percentage of the market that will be captured by fuel cells compared with diesel or gas turbines, the two primary competing technologies. In other words, the forecasts shown in this section define a nominal envelope of market penetration in terms of numbers of units sold by kilowatt size. Expected market penetration will depend on the degree of success achieved in resolving technical issues described in previous paragraphs.

Market segment forecasts are provided with a high degree of confidence because each of these segments has proved to be fairly stable over the last 38 years. Moreover, propulsion and SSG power plant sizes applied to vessels built in the 1990's do not vary greatly within each market segment. A small range of propulsion and SSG unit sizes, less than 2 MW, accounts for most of the power generation requirement in most vessel market segments. A major finding of this study is that a demand for several thousands of units per year will exist if a technologically competitive, commercially viable fuel cell unit capable of producing 250 to 500 kW can be produced. This finding assumes that for applications in the 2 to 4 MW range, ganged, or modularly stacked fuel cell units would be feasible.

6.1 Other Vessel Types

6.1.1 Limited Market Segment

Apart from the thirteen major market segments that appear to dominate the market over the forecast period, there are a number of vessel types on order that were not included in the analysis. These vessels either did not fit into the thirteen large categories that were developed or did represent quantities to justify their own category. Table 6 lists these excluded vessel types and the numbers currently on order. These vessels may become adopters of fuel cell technology during the forecast period.

6.1.2 Offshore Rigs

Offshore oil drilling platforms and other facilities (offshore rigs) are a market segment of interest because they are likely to have a power demand profile that is consistent with the sizes of units that will possibly be feasible during the forecast period. Offshore rigs may also become early adopters of a technology that can offer lower air emissions because 150 rigs, about 28 percent of the world's total, operate in the Gulf of Mexico where operators are sensitive to air quality concerns. By comparison, 85 units operate in the North Sea, 87 units operate in Latin

America, 58 units operate in the Pacific Rim, and 46 and 42 units operate in the Middle East and West Africa respectively. Worldwide, approximately 530 offshore rigs are operational.

Offshore rigs are an attractive application niche, as are U. S. military vessels. Both of these applications are excluded from this study for the same reason. Although they may well become early adopters of a viable new technology, they do not, by themselves, represent sufficient demand to warrant technology commercialization. The focus of this study is to identify the potential based on sufficient volume to justify mass production of fuel cells for the marine market.

Table 6. Vessel Types Not Included In Analysis

Vessel Type	Number On Order	Vessel Type	Number On Order
Barge	9	Pilot Vessel	6
Barge Carrier	1	Pollution Control Vessel	4
Bitumen Tanker	1	Pontoon	6
Buoy/Lighthouse Vessel	23	Research Vessel	22
Cable-Layer	5	Sail Training Ship	1
Crane Ship	1	Salvage Ship	1
Crewboat	4	Standby-Safety Vessel	3
Drilling Ship	12	Supply Vessel	3
Fire-Fighting Vessel	3	Tender (Unspecified)	7
Icebreaker	2	Training Ship	3
Landing Craft	11	Utility Vessel	14
Other Non-Merchant Ships	5	Well-Stimulation Vessel	1
Patrol Vessel	39	Work/Repair Vessel	4

6.2 Economic, Technical And Regulatory Market Drivers

6.2.1 Economic Market Drivers

Vendor cost estimates (goals) for fuel cells vary from $600 to $1,500 per kWe in contrast to $110 to $400 per kWe for generator sets and $425 to $480 for simple gas turbine generator sets. Current capital cost numbers in the literature for fuel cells, diesels, and gas turbines do not include application specific installation costs, which can be significant. Therefore, simple comparison of capital costs for alternative technologies should be viewed as simplistic estimates. For these reasons, efforts to develop a life cycle cost model capable of assessing various propulsion and power generation configurations, and prime mover types are in progress to better estimate the ownership costs of fuel cells and competing technology. Fuel cell operating costs are not yet well defined but need to be driven toward those for diesel engines. It is apparent that life cycle costs must be considered in the evaluation of fuel cell market competitiveness. Important factors include capital cost, power plant efficiency (fuel consumption/cost), cell stack replacement cost (life) and operations and maintenance costs. An

example of the effects of fuel cost, capital cost and operating efficiency on delivered power is shown in Figure 9. The figure illustrates a leveraging effect resulting from high operating efficiency (and high capital costs) of fuel cells in offsetting significantly lower capital costs (and lower efficiency) of a comparable gas-turbine driven device (Runte 1998). As fuel cell development matures, refinements in cost estimating will become available. Another economic factor in the development of markets for fuel cells is the relative strength of various national economies. Appendix C contains a detailed discussion on the affect of negative or positive growth of developed and emerging economies on possible fuel cell markets.

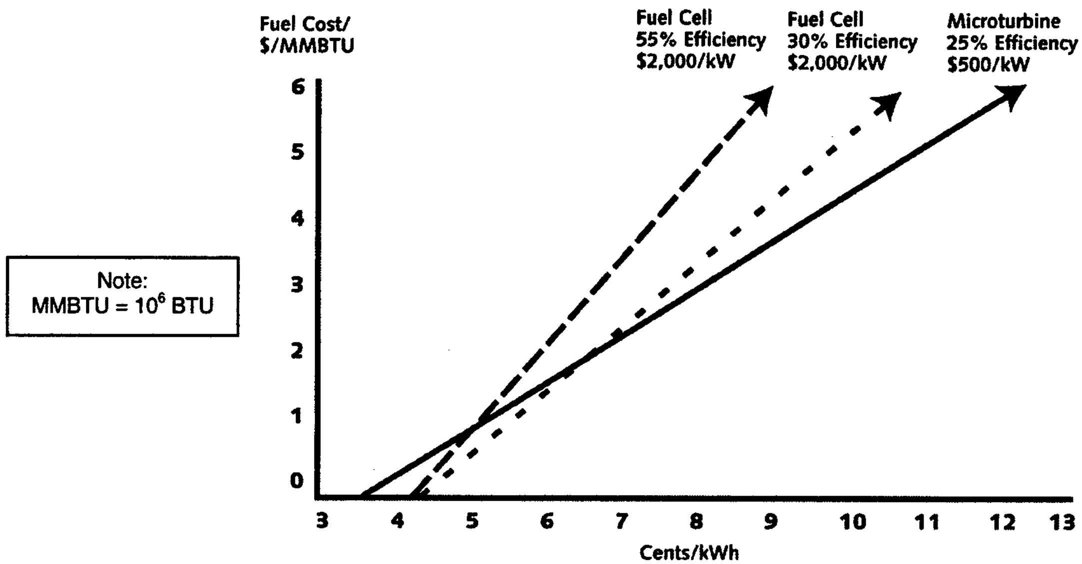


Figure 9. Effects of Fuel Cell Costs, Capital Costs and Operating on Costs of Delivered Power
Source: Gerry Runte, M-C Power Corp, *Five Fuel Cell Myths*, 1998.

6.2.2 Technical Market Drivers

As can be seen from the above discussion, fuel cell efficiencies are an important factor affecting power generation system economics. The benefit of inherently reduced pollutants may also be a major technical, as well as policy, driver. However, as mentioned earlier, other technical issues such as the following need to be resolved:

- Low power densities
- Material operating characteristics
- Start time, and
- Load following characteristics.

6.2.3 Regulatory Market Drivers

With the development of highly efficient fuel cell technologies comes the potential of low- or zero-emissions. Emissions from marine diesel engines account for approximately 4.5 percent of all mobile source oxides of nitrogen and 1percent of particulate matter emissions nationwide. In port cities and coastal areas where marine vessel traffic is

concentrated, the relative contribution of marine vessels to the overall mobile source emissions inventory is higher (U.S. Environmental Protection Agency, November 1998).

The State of California, the U.S. Environmental Protection Agency, International Organization for Standardization (ISO), and International Maritime Organization (IMO) have all issued marine emissions standards and/or procedures in recent years (Southwest Research Institute, March 1999). In 1998, the U.S. Environmental Protection Agency began phasing in federal regulations that will reduce marine-engine emissions by 75 percent by 2005. Furthermore, California may enact regulations requiring that cleaner marine engines be introduced more rapidly. Under a California Air Resources Board (CARB) proposed regulation, typical marine engine emissions would have to be 70 percent cleaner by 2001 and 90 percent cleaner by 2008. Marine engines meeting CARB's proposed regulations in 2008 would generate only one-third as much emissions as engines meeting federal standards (Air Resources Board website). Although these more stringent emissions standards will be in place, marine vessels will continue to represent a significant source of air emissions in the United States coastal areas and waterways unless the vessels are able to utilize cleaner fuels. Furthermore, marine vessels are a significant user of imported hydrocarbon fuels and represent an as yet untapped market for any type of alternative fuels (Cook, 1999).

6.3 Commercial vs. Military Applications

The relative percentages of commercial vessels, U. S. Navy and USCG vessels were shown in Figure 7. From Figure 7, one can conclude that U.S. military vessels comprise about two percent of the world's ships, and as such represent too small a market to be the driving force defining the technology adopted by the world's commercial markets. It is safe to conclude that the requirements of the world's commercial fleet will drive the types of propulsion technology that will be adopted and developed. The commercial fleet will choose a technology that is practical and will be cheaper to buy per kW. The chosen technology will be cheaper because they will be built in commercially large quantities with learning curve reductions in price due to economies of scale. Commercial, off-the-shelf (COTS) power plant technology adopted by commercial marine market segments will make sense for the U. S. Navy and the U. S. Coast Guard because the underlying economic and technical selection criteria will be the same. Moreover, as fuel cell power sources become commercially justifiable, COTS technology can be applied in a way that will allow the military to adopt design specifications that are consistent with civilian regulatory trends.

6.4 Fuel Cell Demand Potential

For both primary propulsion and SSG, algorithms were written to sort the LMIS power plant data by size. These power plant data were sorted for all 13 market segments. Initial units of analysis were kilowatt (kW) rating for SSG power and megawatts (MW) for propulsion.

The first iteration of sorting yielded the surprising result that power rating for both propulsion and SSG were tightly clustered around specific power rating sizes for all major market segments. The analysis was refined and new sorts were run based on preliminary results to segregate power ratings and develop reduction categories that were the most appropriate for SSG and propulsion.

For example, initial sorting demonstrated that many propulsion power units are rated at 2 MW and below, independent of market segment analyzed. Some propulsion units are very large, 20 MW and greater, but there are relatively few installations in this power range. Once this result was obtained, resorting the data with higher 'granularity' (or more detail within power levels of interest) was completed.

By developing reasonable expectations for the numbers of vessels forecast by market segments, equations (1) and (2) (see paragraph 5.3.3) were used to calculate market potential. But such potential is the upper bound on total market segment demand. Another way of interpreting the market potential is to say that it represents the numbers of fuel cells that will be applied for primary propulsion and ship set generator application in each market segment if 100 percent of new ships constructed in that segment use fuel cells.

Analysis of propulsion units demonstrated that power increments could be sorted into common size categories (MW) across market segments. Figure 10 shows that such sorting was clearly successful. Figure 10 is a plot of all the world's oil tankers. Based on current practice for sizing propulsion units, the forecasts in Figure 10 show three solid bars for each power level category. For example, for propulsion power in the range labeled "<2MW", three solid bars represent the numbers of main propulsion units that will be demanded by the market in the years 2001-2005, 2006-2010, and 2011-2015 respectively. One can see that in the five years from 2001 through 2005, the oil-tanker market segment will demand approximately 325 propulsion units, with a power rating less than 2 MW. With the exception of the power range from 10 to 20 MW, Figure 10 also shows that most propulsion power units will be less than 4MW. If a viable fuel cell can be produced at high volume in a size of about 500kW, modularly stacked or ganged units could satisfy demand in each of the 5 year time ranges for up to about 1,500 units for the oil tanker segment. Similar demand projections can be made for the other 12 major market segments shown in Appendix C.

Results shown in Appendices D and E show that sorting on common power rating categories (MW) for main power was successful for all major markets. Results for SSG power followed the same procedure, and also demonstrated tight clustering of power required by kW size. SSG results for oil tankers are shown in Figure 11. SSG results for all market segments are shown in Appendices F and G. From Figure 11, one can see that a fuel cell rated at 500 kW could satisfy the demand for up to 600 units in the, "<500kW" range. Demand in the 501-1500 kW range could account for two to three times that demand through the application of modularly stacked units. Because the power demands are so tightly clustered below 1500 kW, production of many different models of fuel cells with power ratings different from 500 kW seems not to be necessary.

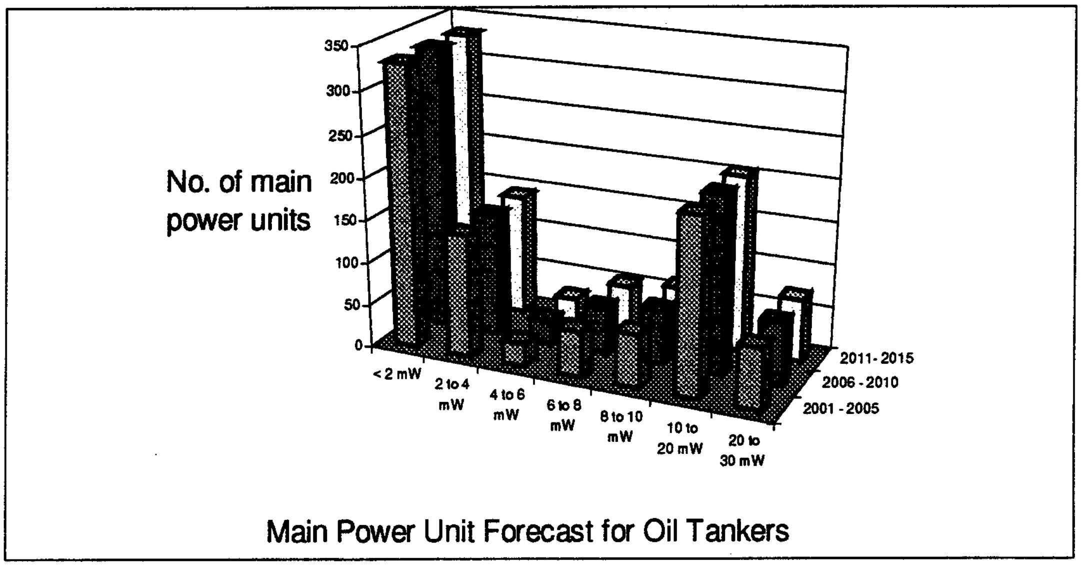


Figure 10. Size of Propulsion Power Units Forecast For Oil Tankers

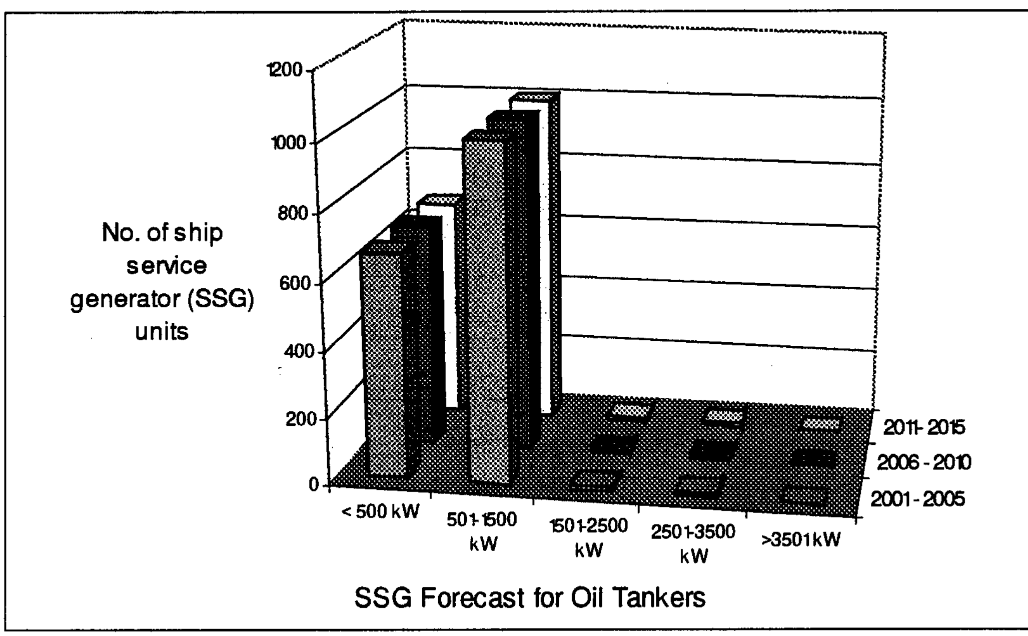


Figure 11. Size of SSG Units Forecast For Oil Tankers

Successful identification of common size categories is important because such market homogeneity allows integration across market segments, both in terms of aggregate quantity of power units demanded over the forecast period and power rating. Clustering by power

Successful identification of common size categories is important because such market homogeneity allows integration across market segments, both in terms of aggregate quantity of power units demanded over the forecast period and power rating. Clustering by power application is shown clearly in Figures 12 and 13 for power units and ship service generators respectively. In Figures 12 and 13, demand has been aggregated over all 13 market segments.

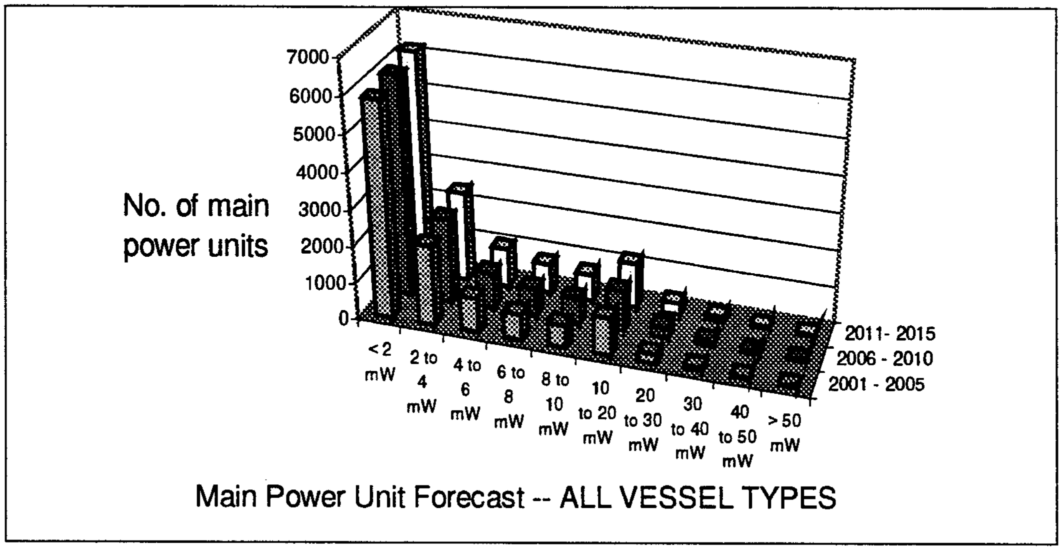


Figure 12. Main Power Units Distributed by MW Rating Forecast For All Market Segments

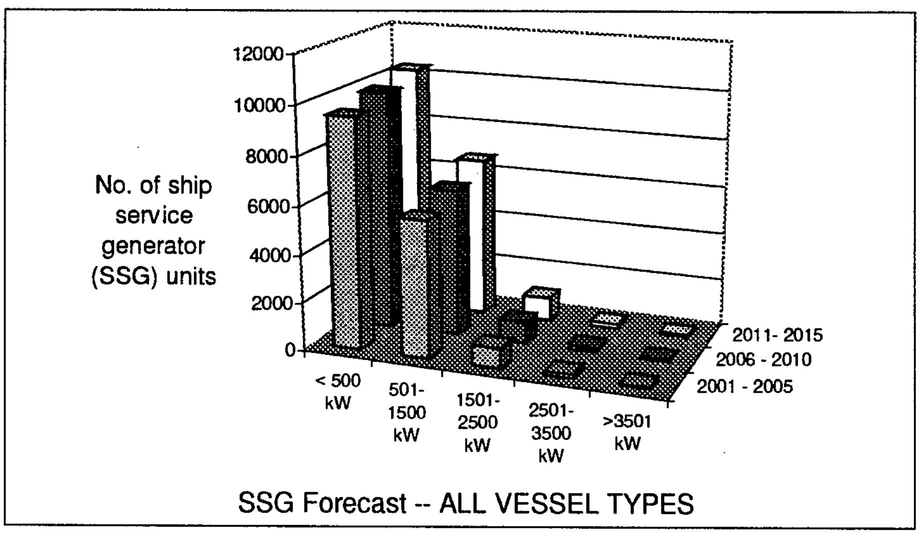


Figure 13. SSGs Distributed by kW Rating Forecast For All Market Segments

Figures 12 and 13 show that certain power ratings comprise attractive size categories for production of those power levels which can then be used for both main propulsion and SSG applications. The conclusion drawn from inspection of Figures 12 and 13 is the same as that drawn from Figures 10 and 11. Power demand for both main propulsion and SSG applications is concentrated in narrow kW ranges and total demand for 500 kW nominal power module exceeds 30,000 units in each of the 5 year intervals.

Added detail for selected market segments is presented in Figures 14 through 18. These five figures provide market demand detail for selected markets for only those propulsion power applications that are less than 2 MW. For each of these segments, numbers of main propulsion power units are shown in integer multiples of 250 kW. For example, Figure 14 shows that demand for 207 main propulsion units are forecast in the size range of 500 kW to 750 kW. If a technically viable, market competitive fuel cell were available in the marketplace, this single size range for only the tugboat segment would demand between 414 and 621 individual 250 kW power units. For all sizes shown in Figure 14, tugboat demand for a viable fuel cell for propulsion would be between 3,800 and 4,800 units.

One can see from Figures 15 through 18 that the demand for a viable 250kW fuel cell is many thousands of units. And these five figures highlight only the demand for main propulsion units that are less than 2 MW in size for a limited number of market segments. Applying such a 250 kW fuel cell to larger power applications might be feasible if design specific modular, or "stacked," designs could be developed. Alternatively, larger size fuel cells could be introduced. Eventually, product lines of fuel cells that range in size much as diesel power units do now could be feasible.

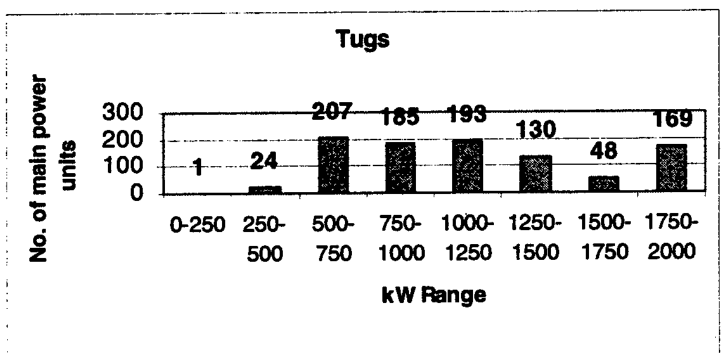


Figure 14. Tug Main Power Unit kW Breakdown

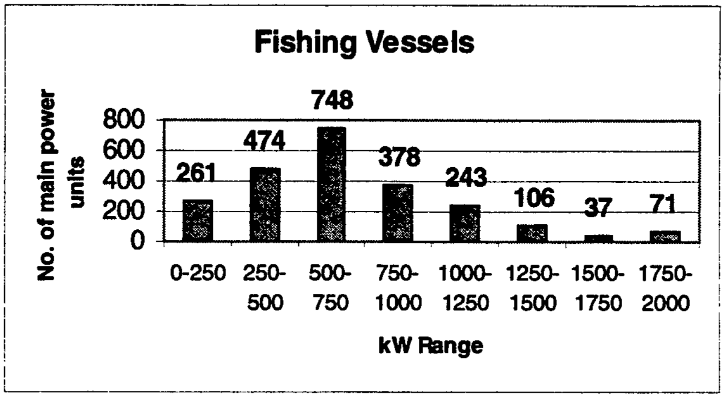


Figure 15. Fishing Vessel Main Power Unit kW Breakdown

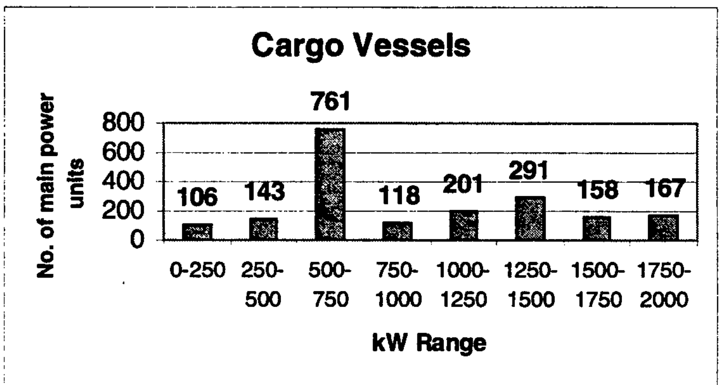


Figure 16. Cargo Vessel Main Power Unit kW Breakdown

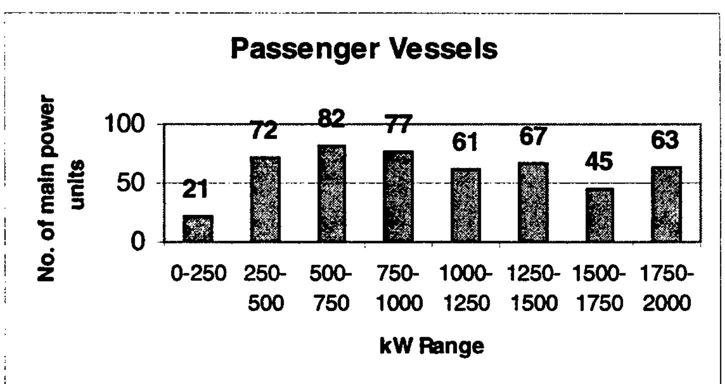


Figure 17. Passenger Vessel Main Power Unit kW Breakdown

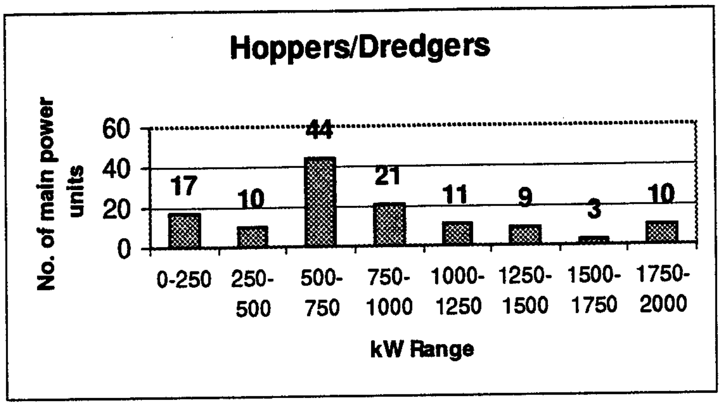


Figure 18. Hopper/Dredger Main Power Unit kW Breakdown

Maximum potential demand for marine applications of fuel cells over the 15 year forecast period for all size units in the thirteen market segments for both main propulsion and SSG amounts to tens of thousands of units as shown in Appendices C through G. The actual number of units demanded will depend on the sizes of fuel cells that can be delivered to the marketplace and the relative market penetration of fuel cells compared to alternatives such as diesel engines.

6.5 Structured Interviews

To gain some perspective on the potential acceptance of fuel cells for marine applications, telephone interviews were conducted with shipbuilders, design agents and vessel operators in order to identify which criteria they judged as most important to adoption of fuel cells. Eight criteria were chosen and were divided into pairs. The researcher then inquired which of the pair was more important. Through a process of elimination, the most important criteria were to emerge in a "waterfall" manner.

The fuel cell acceptance criteria explored included:

- Power plant efficiency over a wide range of loads
- Noise, vibration
- Environmental emissions reduction
- Power plant weight (lb./kW)
- Power plant physical size (ft3/kW)
- Power plant capital cost (cost to buy)
- Power plant maintenance cost (cost to fix)
- Power plant operating cost (overall cost to run).

Although the sample was relatively limited, it does provide an indication of how some industry members tend to, or may, react to the use of fuel cells.

A total of 14 contacts were attempted. Four did not return phone calls; one was completely disinterested in discussing the subject. The remaining nine (including seven shipbuilders/designers) provided information ranging from courteous comments/inquiries, hurried conversation to some incisive commentary as was the case for fishing boat operators.

6.5.1 Shipbuilders and Design Agents

The responses can be briefly summarized as follows:

- Most were unfamiliar with fuel cells and that they were being considered for marine applications. (At best they were peripherally knowledgeable.)
- Cost containment was very high on their list of concerns.
- Design and operating orthodoxy appears to be a major consideration; being comfortable with the known (i.e. diesels) and fear of the unknown.

Some other thoughts/questions and musings included:

- What are effects on general equipment arrangements?
- What are effects on the ship's sea keeping stability?
- Volume considerations. Power plants are one thing; balance of plant is another.
- Ductwork implications; uptake/intake sizes, etc. For example, gas turbines require significant added volume to accommodate ductwork. What is the effect of fuel cells?
- What are cooling water requirements relative to combustion engines? Some engines require significant cooling water.

6.5.2 Fishing Boat Operators

Fishing boat operators brought some hands-on realities to the fore. Their main concern was, can use of the new technology:

- Improve productivity or,
- Allow them to gain a competitive advantage?

Capital costs, life cycle costs, operation and maintenance costs were subordinated to the two items above. As an example, use of sonar in fish detection was quickly adopted after some fishing boat early-adopter. Capital costs, operating costs and life cycle costs of the sonar systems all exceeded the cost of the alternative: no fish finding sonar. Yet the entire fishing industry has adopted the sonar technology to improve productivity and/or maintain a competitive position in the industry. Moreover, the fishing industry has opted to adopt a number

of higher-cost alternative technologies over the last several decades to increase productivity or for competitive reasons. The fishing boat owners/operators interviewed expect two possible drivers for fuel cell adoption.

- Operation in U.S. coastal waters under stringent air quality regulations may require operators to move away from the combustion of traditional fuels.
- A reduction in noise propagation may enable closer approach to fish schools by fishing vessels.

The second point, if demonstrated to be significant by early adopters, may result in large-scale adoption by fast-followers in the fishing industry. The driver for adoption in this later case would be increased productivity in the form of increased yield.

7.0 MARKET POTENTIAL – CONCLUSION

7.1 Application Forecasts

Statistics for 1993 indicate completion of at least 1700 vessels to probably more than 2000 vessels, totaling almost exactly 20M gross tons. To this number of completions must be added naval vessels and many small craft. The tonnage figure, which is not likely to be far in excess of 20MT, is more pertinent as far as power requirements are concerned. This is not a high growth area, but the market is rather an aggregate of some 800-900MT for the 1990-2020 period.

The overall average power requirement for the marine industry is thought to be about 0.8kW/T, giving an aggregate requirement of 600-700GW over the research period. However, few expect fuel cells to displace established prime movers from large parts of the marine market. From Appendix A, interest was reported to be centered on particular applications such as submarines and gas carriers, with occasional use in other areas, both for propulsion and for auxiliary power. Given the size of the market, even low penetration can yield an important market for marine fuel cells.

7.1.1 Naval Systems

Interest in use of fuel cells has abated somewhat in the important area of submarine propulsion, reflecting lower support for most defense activities. Methanol/LOX propulsion will enable sustained low-noise submerged operation, and is seen as a particularly promising application for fuel cells, although one which is now less likely to be developed in the short term. It is understood that most of the design studies and prototypes/trials have been based on PEM fuel cell technology, with modules up to tens of kW and assessments up to about 1 MW.

Other underwater prospects at lower powers include propulsion for remotely operated vessels (both commercial and naval) and long range torpedoes/underwater missiles, where fuel cells would provide cruise or loitering power supplemented by high power-density batteries for attack phases.

Use of fuel cell propulsion and auxiliary power is technically feasible for various naval surface vessels. However, prospects for success on a wide scale seem slim at this stage (Source: EscoVale Consultancy Services Reports). The emergence of the "electric navy" is seen as a driving force, not just in the naval requirement itself, but also in developing the technology to the level where it can be applied more widely.

The U.S. Navy is considered to have the most highly developed electric propulsion program. However, advanced gas turbines are the only serious contenders for surface warship propulsion within our timeframe, with unit power requirements at the tens of MW level. Important factors for choosing gas turbines are familiarity with gas turbines and the ability to change-out power modules quickly. Advanced gas turbines are seen as a radical improvement on existing propulsion systems, but one with a low and controllable risk. New technology, such as a high power fuel cell, could add a decade to the lead-time for a project such as a major surface warship.

The total naval requirement for prime movers over the 1990-2020 period is estimated at 30-40GW, of which more than 10 percent (say 5GW) can be attributed to auxiliary power rather than to propulsion. The requirements for auxiliary power are varied and increasing. There are no specific developments which could lead to large-scale use of fuel cells in this application, but there are opportunities, given the substantial progress which fuel cells are making in land based power generation.

While the potential accessible market segment in the naval sector is comparatively small, non-nuclear submarine and submersibles are an attractive area where fuel cells are likely to be considered. However this represents only a few hundred MW of capacity over the research period. This compares with a 30-year total for naval electric propulsion which may exceed 5GW, according to some estimates. However, there are short term opportunities for small fuel cells (up to about 20kW), but in specialized submersibles rather than high volume weapons systems.

Current information suggests that in naval applications the potential market will prove disappointing. As fuel cells will still have to compete with well-established and increasingly effective prime movers, it seems unwise to assume that this potential will yield an actual market of more than say 200-250 MW in aggregate over the period to 2020.

7.1.2 Commercial Marine

Outside the naval area, the established competition at high power levels comes mainly from medium and low speed marine diesels. These are highly efficient (around 40 percent, peak), and are expensive by reciprocating engine standards, although not when compared to a fuel cell/electric propulsion alternative. Realistic prospects are therefore likely to be concentrated in areas where electric propulsion is already viable, or will become so, together with those where the vessel duty integrates well with use of fuel cells. LNG carriers represent an example of the latter, with the possible future development of bulk hydrogen carriers being of particular interest. Opportunities within the general purpose marine market will be more diffuse, but are worth considering because of the large size of the sector.

Current applications for high power electric propulsion (apart from naval craft) include oil industry vessels and others where station-keeping is critical; ferries, where flexibility and maneuverability are important; ice-breakers; and passenger cruise liners. A factor of great importance in both naval and commercial applications is the general increase in the ratio of service loads to propulsion power, which makes it more appropriate to consider a central power station approach, where propulsion is just one of several duties.

Cruise ships represent a good example of this, where low levels of noise and vibration are also critical. At lower power requirements, similar factors apply at the end of the private yacht/cabin cruiser/charter vessel market. The luxury segment of this business area is quite large, measured in hundreds of units annually. It is one where budgets could stretch to cover realistic fuel cell costs.

Opportunities in electric propulsion could be considered in much the same light as those in remote site power generation, where it was concluded that roughly 10 percent of additions in the 1 –30 MW range should be regarded as potentially accessible to fuel cells. One

advantage in the marine area is that electric propulsion is a highly specialized area, where designers and operators alike will be better disposed to new technologies than a typical operator of land-based plant. In this case, fuel cells are expected to have an edge, in terms of weight, if the competition comes from low speed diesels. In addition, the ability to distribute the power source around the vessel may be a very attractive design feature.

Against this, fuel cells have difficulty in matching diesel efficiency on low grade fuels, with very little prospect of high temperature fuel cells suitable for MW marine applications before 2020. Efficiency is exceptionally important in marine applications, even in specialized vessels using electric propulsion where there is a trade-off of efficiency against other performance aspects. In view of this, it is believed that fuel cells will be given serious consideration in less than 10 percent of the electric propulsion market.

However, there are specialized applications where efficiency does not apply. If marine transportation of bulk hydrogen becomes a reality, fuel cells are expected to be the preferred power source. Natural gas carriers represent another opportunity for FC propulsion, but in this case, one where other technologies are the front runners. Auxiliary electric power generation represents another very substantial application, where fuel cells may have a future role. The requirement averages more than 1 gW/yr and perhaps 50 gW in total from 1990 to 2020.

The use of fuel cells for auxiliary power is unlikely to bring with it the same advantages that apply for land-based operation. Primary considerations for auxiliary power sources are for equipment that is very robust, familiar, and fuel tolerant. High temperature marine fuel cells for auxiliary use will take longer to develop than their land-based counterparts. While use of fuel cell auxiliaries is unlikely to become common practice, the size of the application is such that this could still be a viable market for fuel cells.

7.2 Market Segment Penetration Rate Forecasts

As can be seen from Appendix G, some market segment trends are growing (e.g. container ships), while other market segments are flat or cyclical (e.g. oil tankers, cargo ships).

7.2.1 Fuel Cell Market Penetration

Since land based fuel cell applications have received more funding and research attention than marine applications and are less subject to specialized constraints (e.g. kW/Ft^3 constraints), it is reasonable to expect that land based fuel cells are likely to be deployed in commercial quantities before marine use is widely adopted. But the same technical, economic and especially regulatory drivers will influence commercial status in both marine and land based applications in roughly the same time frame.

7.2.2 Market Penetration Rate for Light Duty Vehicles

Figure 19 summarizes projections of fuel cell market penetration for, as an example, light duty vehicles in the United States. These projections are from a variety of sources. The Ballard Fuel Cell Stack projection and the initial commercial date forecast by Daimler Benz both show an initial penetration in about the 2005 time frame. Directed

Technologies has developed a high/low range of adoption scenarios as shown in Figure 19. Directed Technologies anticipates substantial volume to start to build between the year 2010 and 2013. CALSTART has developed its own projection for other studies as shown by the dotted line. Regardless of which forecast is used, significant land applications are anticipated during the forecast period of interest in this study.

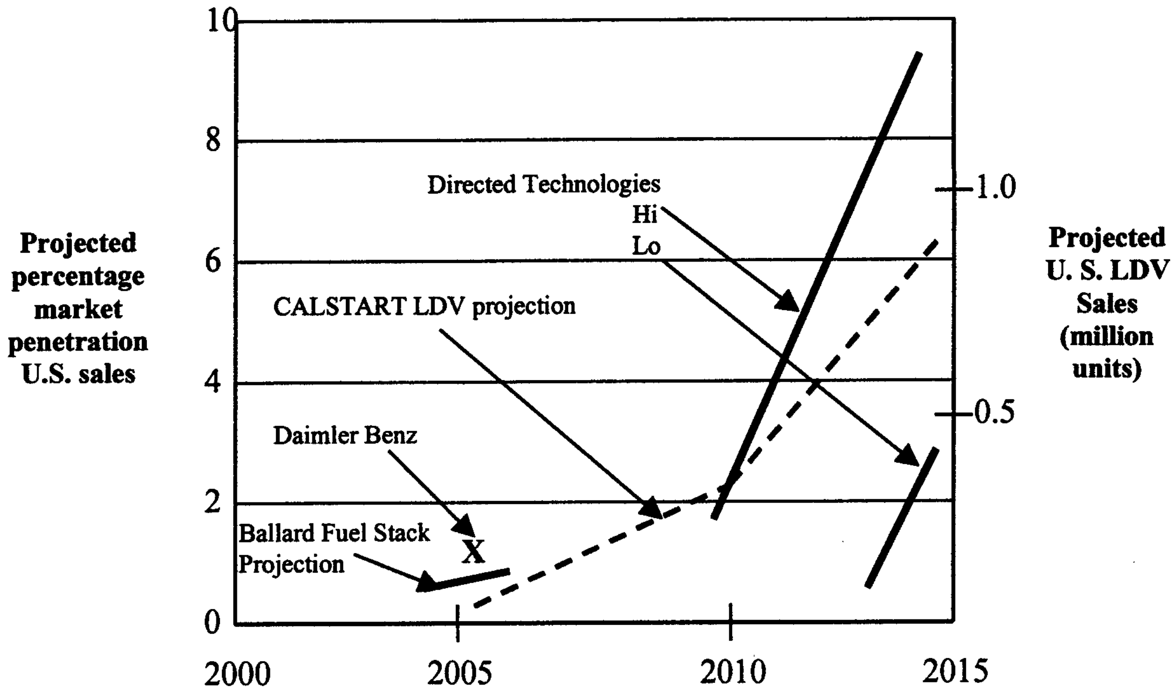


Figure 19. Fuel Cell Market Forecasts For Light-Duty Vehicles

7.2.3 Marine Market Penetration

While it may be reasonable to expect that marine market penetration may lag land applications, it is reasonable to think that the lag will be relatively small. Therefore, it is likely that some significant level of market penetration will occur in commercial marine application before the year 2015.

Because the approach used in this analysis was to provide bounds for the projected market penetration based on demands for new ship construction, it is not possible to provide absolute numbers for future demands. Combining the data types discussed above and shown in Figure 19 with the forecasted demand for main power units and SSG shown in Figures 12 and 13, repeated below, leads to the following conclusion. If fuel cell technology can be made commercially justifiable with unit power output between 250 kW and 500 kW, the marine market potential for fuel cells could total tens of thousands of units sold by the year 2015.

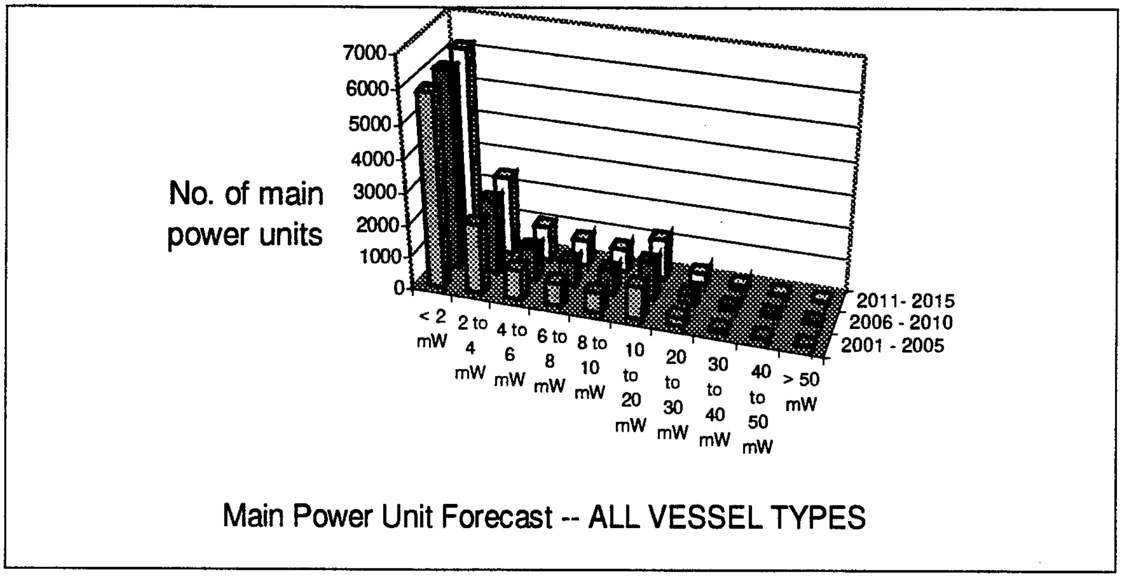


Figure 12 (Repeated). Main Power Units Distributed by MW Rating Forecast For All Market Segments

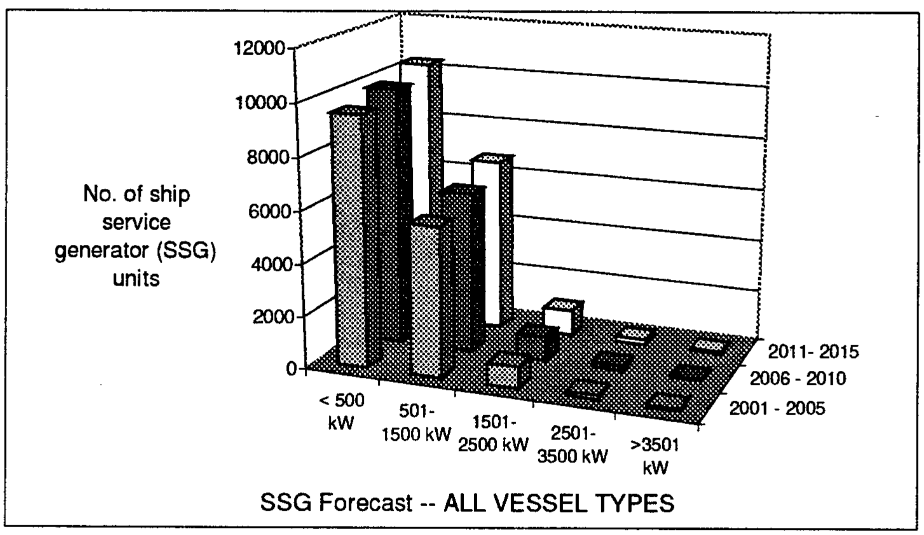


Figure 13 (Repeated). SSGs Distributed by kW Rating Forecast For All Market Segments

8.0 REFERENCES

Abens, Sandy, ERC. (April 15,1999). Personal communication.

Air Resources Board. (December 1998). Proposed New Regulations for Gasoline Marine Engines. Available http://www.arb.ca.gov/msprog/marine/perswc.

Allen, Ashey, Gore, Woerner and Cervi. (January 1998). Marine Applications of Fuel Cells. Naval Engineers Journal.

Appleby, A. John. (1999, July). The Electrochemical Engine for Vehicles. Scientific American. Vol. 281, No. 1, p. 74-79.

Bolind, A. M.. (June 24, 1998). An Evaluation of Fuel Cells for Commercial Ship Applications. BS thesis in Naval Architecture, Webb Institute, Glen Cove, NY.

Cook, Zak. (February 1999). Seaport Liquid Natural Gas Study. CALSTART.

(January 1999). Diesel Delivers Economies. The Motor Ship.

(December 1998). Fuel Cells: Applications and Opportunities. EscoVale Consultancy Services, Report No. 5010.

(December 1998). Fuel Cells: The Source Book. EscoVale Consultancy Services, Report No. 3400.

(July 1992). Forecast International/DMS Market Intelligence Report.

Gerry Runte. (1998). Five Fuel Cell Myths. M-C Power Corp.

Goubault, Greenberg, Heidenreich, and Woerner. (May 1994). Fuel Cell Power Plants for Surface Fleet Applications. Naval Engineers Journal.

Lloyd, Alan C. (1999, July). The Electrochemical Engine for Vehicles. Scientific American. Vol. 281, No. 1, p. 80-86.

(February 1999). Kawasaki Heavy Industries webpage. Available http://www.khi.jp.

(February 1999). Lloyd's Maritime Information Services Data.

MAN webpage, www.manbw.dk, February 1999.

Moore, T.M.. (Mar/Apr 1998). Emerging Markets for Distributed Resources. EPRI Journal.

Department of Energy, California Energy Commission, California Air Resources Board, and South Coast Air Quality Management District. (November 20, 1998). Proceedings of the Fuel Cell Reformer Conference.

(July 1998). Propulsion Machinery Working Group Summary. Marine Technology, p. 149.

Schmal, Kluiters, Ligtvoet, and Barendregt. (Nov 16-19, 1998). Polymer Fuel Cell Testing for Naval Ship Applications. 1998 Fuel Cell Seminar, Palm Springs, CA, p. 679-682.

(September 1979). Shipbuilding and Marine Engineering Annual.

(March 1999). CNG Ferry Feasibility Study. Southwest Research Institute.

Steinfeld, Sanderson, Woerner and Cervi. (Nov 16-19, 1998). Concept Development of A Ship Service Fuel Cell. 1998 Fuel Cell Seminar, Palm Springs, CA, p. 379-382.

Tharp, M., MTI. (March 1999). Personal communication.

U.S. Environmental Protection Agency. (November 1998). Notice of Proposed Rulemaking (EPA-420-F98-044).

Valenti, Michael, Associate Editor. (December 1997). Molten-Carbonate Fuel Cells Go Navy. Mechanical Engineering, p. 78-79.

(February 1999). Wartsila webpage. Available http://www.wartsila-nsd.com.

APPENDIX A.
MARINE FUEL CELL APPLICATIONS AND FORECASTS

A-1. APPLICATIONS AND FORECASTS

Marine applications are seen as prospective users of fuel cells. Statistics for 1993 indicate completion of 1700 vessels totaling almost exactly 20M gross tons. The figures are said to be undercounted in some countries, especially towards the lower cut-off of 100T. The number of completions probably exceeds 2000, to which must be added naval vessels and many small craft. The tonnage figure, which is not likely to be far in excess of 20MT, is more pertinent as far as power requirements are concerned. This is not a high growth area, but the market is rather an aggregate of some 800-900MT over the 1990-2020 period.

Marine power requirements relate to vessel size and duty. For the largest tankers and similar ships, specific powers of less than 1 kW/T apply (down to about 0.3kW/T in some cases). A figure of 1 kW/T is fairly typical for smaller vessels (below 10,000T say) but rising sharply below about 1,000T. More specialized commercial vessels, such as passenger liners, may require 2-3kW/T, while naval craft can easily exceed 5kW/T.

The overall average for the marine industry is thought to be about 0.8kW/T, giving an aggregate requirement of 600-700GW over the research period. However, few expect fuel cells to displace established prime movers from large parts of the marine market. Interest tends to be centered on particular applications such as submarines and gas carriers, with occasional use in other areas, both for propulsion and for auxiliary power. Given the size of the sector, even occasional use can yield an important market.

A-2. NAVAL SYSTEMS

Interest in use of fuel cells has abated somewhat in the important area of submarine propulsion, reflecting lower support for most defense activities. Methanol/LOX propulsion will enable sustained low-noise submerged operation, and is seen as a particularly promising application for fuel cells, although one which is now less likely to be developed in the short term. It is understood that most of the design studies and prototypes/trials have been based on PEM fuel cell technology, with modules up to tens of kW and assessments up to about 1 MW.

Other underwater prospects at lower powers include propulsion for remotely operated vessels (both commercial and naval) and long range torpedoes/underwater missiles, where fuel cells would provide cruise or loitering power supplemented by high power-density batteries for attack phases. PEM fuel cells again seem to be the preferred technology.

Use of fuel cell propulsion and auxiliary power is also feasible for a variety of naval surface vessels, but prospects for success on a wide scale seem slim at this stage. The emergence of the "electric navy" is seen as a driving force, not just in the naval requirement itself (where there are already important applications for electric propulsion in silent-running operation for example), but also in developing the technology to the level where it can be applied more widely.

The U.S. Navy is considered to have the most highly developed electric propulsion program. However, advanced gas turbines are the only serious contenders for surface warship propulsion within our timeframe, with unit power requirements at the tens of MW level. Familiarity with gas turbines is a very important factor, as is the ability to change-out power modules in a matter of hours. Advanced gas turbines are seen as a radical improvement on existing propulsion systems, but one with a low and controllable risk. The introduction of a new technology such as a high power fuel cell could add a decade to the lead-time for a project of this type. Furthermore, fuel cells are said to fall well short in critical areas such as power density, even when offsets from reduced requirements for noise suppression, very low thermal emissions, and simpler control are taken into account.

Some of the objections to fuel cells might be overcome with a hybrid solution, such as using high power gas turbines together with a fuel cell for relatively low power cruising, quiet running, and utilities. This would still be a multi-MW unit, but the extra bulk of a fuel cell would be much less of a penalty if it was providing, say, 25 percent of the total capacity. The extra space required might be fully offset by reduced fuel storage requirements, assuming that fuel cells retain a distinct efficiency advantage over advanced gas turbines. This is certainly not a foregone conclusion for low temperature fuel cells operating on naval fuels, since the target is to achieve more than 40 percent efficiency from the gas turbine package. There is no information at this time to suggest that a hybrid approach is being given active consideration at present, or that it is being strongly advocated.

The total naval requirement for prime movers over the 1990-2020 period is estimated at 30-40GW, of which more than 10 percent (say 5GW) can be attributed to auxiliary power rather than to propulsion. The requirements for auxiliary power are varied and increasing. There are no specific developments which could lead to large-scale use of fuel cells in this application, but it would be surprising if there were no opportunities, given the substantial progress which fuel cells will be making in land based power generation over this period.

Results to date do suggest however, that the potentially accessible market in the naval sector is comparatively small. The non-nuclear submarine and submersible sector is an attractive area, where fuel cells are likely to be considered in most cases, perhaps representing a few hundred MW of capacity over the research period. This compares with a 30-year total for naval electric propulsion which may exceed 5GW, according to some estimates. However, there are short term opportunities for small fuel cells (up to about 20kW), but in specialized submersibles rather than high volume weapons systems.

Current information suggests that the potentially accessible market in naval applications will prove disappointing. For example, it is difficult to justify a figure as high as 1000 MW over the period to 2020, representing the total where fuel cells will be given serious consideration (mainly in submarines and auxiliary power). However, fuel cells will still have to compete with well-established and increasingly effective prime movers, and thus it seems unwise to assume that this potential will yield an actual market of more than say 200-250 MW in aggregate over the period to 2020.

A-3. COMMERCIAL MARINE

Outside the naval area, the established competition at high power levels comes mainly from medium and low speed marine diesels. These are highly efficient (around 40 percent), and are expensive by reciprocating engine standards, although not when compared to a fuel cell/electric propulsion alternative. Realistic prospects are therefore likely to be concentrated in areas where electric propulsion is already viable, or will become so, together with those where the vessel duty integrates well with use of fuel cells. LNG carriers represent an example of the latter, with the possible future development of bulk hydrogen carriers being of particular interest. Opportunities within the general purpose marine market will be more diffuse, but are worth considering because of the large size of the sector.

Current applications for high power electric propulsion (apart from naval craft) include oil industry vessels and others where station-keeping is critical; ferries, where flexibility and maneuverability are important; ice-breakers; and passenger cruise liners. A factor of great importance in both naval and commercial applications is the general increase in the ratio of service loads to propulsion power, which makes it more appropriate to consider a central power station approach, where propulsion is just one of several duties.

Cruise ships represent a good example of this, where low levels of noise and vibration are also critical. It is thought that around 20 cruise ships with electric propulsion have now been built or ordered, with an aggregate capacity on the order of 500 MW. At lower powers, similar factors apply at the end of the private yacht/cabin cruiser/ charter vessel market. The luxury segment of this business area is quite large, measured in hundreds of units annually. It is one where budgets could stretch to cover realistic fuel cell costs, and there are likely to be several factors of greater significance. These include the need to bring physical size down closer to the levels of a high speed marine diesel engine and to match the level of local support provided by engine companies (this assumes that fuel cells can emulate diesels in terms of reliability, which is probably the most critical factor).

Opportunities in electric propulsion could be considered in much the same light as those in remote site power generation, where it was concluded that roughly 10 percent of additions in the 1 -30MW range should be regarded as potentially accessible to fuel cells. One advantage in the marine area is that electric propulsion is a highly specialized area, where designers and operators alike will be better disposed to new technologies than a typical operator of land-based plant, provided that there are perceived benefits. In this case, fuel cells are expected to have an edge, in terms of weight, if the competition comes from low speed diesels. In addition, the ability to distribute the power source around the vessel may be a very attractive design feature.

Against this, fuel cells are expected to have real problems in matching diesel efficiency on low grade fuels, with very little prospect of high temperature fuel cells suitable for MW marine applications before 2020. Efficiency is exceptionally important in marine applications, even in specialized vessels of the types which opt for electric propulsion, and where there is more scope for trade-off against other performance aspects. In view of this, it is believed that fuel cells will be given serious consideration in less than 10 percent of the electric propulsion market.

However, there may be specialized applications where this does not apply. For example, if marine transportation of bulk hydrogen becomes a reality, fuel cells are expected to be the preferred power source. There is very little chance that this will occur on a large scale within our timeframe, although sizeable demonstration projects are feasible within this period. Such projects would require a fleet of only three or four vessels to serve pilot demonstrations in Europe and Japan (less than 100 MW in total, over the 2010-2020 interval).

Natural gas carriers represent another opportunity for FC propulsion, but one where other technologies are the front runners. LNG carriers generally use conventional reciprocating engine propulsion systems, with dual fuel engines as an alternative. Proposals have also been made for use of gas turbine propulsion packages, but it is unclear if any which have been implemented. It is believed that reasons include the relatively low efficiency of present gas turbines for this type of application and the fact that gas availability as a result of normal evaporation would not cover the propulsion requirement. This has not been mentioned as a factor with regard to fuel cell propulsion of hydrogen carriers, but it is assumed that the fuel availability as a result of transfer losses may be proportionately higher in this case.

Auxiliary electric power generation represents another very substantial application, where fuel cells may have a future role. The requirement averages more than 1 GW and perhaps 50 GW in total from 1990 to 2020. The central generating plant provides auxiliary power on vessels opting for electric propulsion (apart from emergency sets). In other vessels, dedicated auxiliary diesel generating sets are commonly employed, although there is a trend towards use of a constant speed power-take-off arrangement to utilize the propulsion engines for this purpose. This reduces the size of the plant and may enable use of lower grade fuel (although auxiliary sets seldom require premium fuel).

The use of fuel cells for auxiliary power is unlikely to bring with it the same advantages that apply for land-based operation. Noise, vibration and environmental considerations are seldom critical; the fuel required for power generation is usually dwarfed by that used for propulsion; equipment needs to be very robust, familiar and fuel tolerant; and high temperature marine fuel cells will take longer to develop than their land-based counterparts. In these circumstances, use of fuel cell auxiliaries is unlikely to become common practice. However, the size of the application is such that this could still be of some importance.

While the commercial marine market is of large magnitude, it is not one where fuel cells will make rapid inroads. For the purposes of this assessment, it is assumed that consideration will be given to fuel cells in applications totaling more than 1000 MW over the research period. This might comprise 100 MW of gas tankers, around 5-10 percent of electric propulsion, and a modest contribution from auxiliary power. There is probably sufficient scope within this potentially accessible market to yield an overall requirement of about 300 MW, or rather more than that attributed to the naval requirement.

A-7. REFERENCES

(December 1998). Fuel Cells: Applications and Opportunities. EscoVale Consultancy Services, Report No. 5010.

(December 1998). Fuel Cells: The Source Book. EscoVale Consultancy Services, Report No. 3400.

[This page intentionally left blank.]

APPENDIX B.
FUEL CELL MARKET OVERVIEW

B-1. THE PERIOD TO 1999

Aggregate installations over the period up to and including 1999 are expected to amount to a little over 800 MW, at a rate moving up from less than 50 MW in 1995 to more than 250 MW in 1999 (see Table B-1 and Figure B-1). It will come as no surprise that the entry markets are in stationary power, with the sub-1MW sector accounting for just over half of the total. Forecast shows higher power units finding increasing application towards the end of the decade (although not in the top rating band), to contribute over 40 percent of the total. Most of the remainder is attributed to units below 10 kW, seen as the other area to achieve commercial status during this period.

Territorially, North America accounts for virtually half the total, followed by the Asia-Pacific market at almost 40 percent. Western Europe makes a comparatively small contribution at this stage, with less than 15 percent of all installations.

As an order of magnitude figure, the value of fuel cells supplied over this period is put at around $1.8 billion. Of this, MCFCs account for approximately 35 percent, and PEMFCs account for approximately 10-15 percent.

	Capacity (MW)	Share (%)
APPLICATION: Total	800-850	100
>30MW	...	...
1-30MW	350-375	43-45
10kW-1MW	~425	51-53
<10kW	~30	3-4
Rail & Marine	...	...
Commercial Vehicles	<5	<1
Passenger Cars	...	...
Other Mobile	...	...
TERRITORY Total	800-850	100
North America	400-425	48-50
West Europe	100-125	12-14
Asia-Pacific	300-325	36-38%
Other Areas	...	...
TYPE Total	800-850	100
PAFC	500-525	61-63
AFC	<5	<1
PEMFC	50-60	~7
DMFC	...	...
SOFC	10-20	~2
MCFC	225-250	28-30

Table B-1. Fuel Cell Markets in the 1990's
Source: EscoVale Consultancy Services Report No. 5010

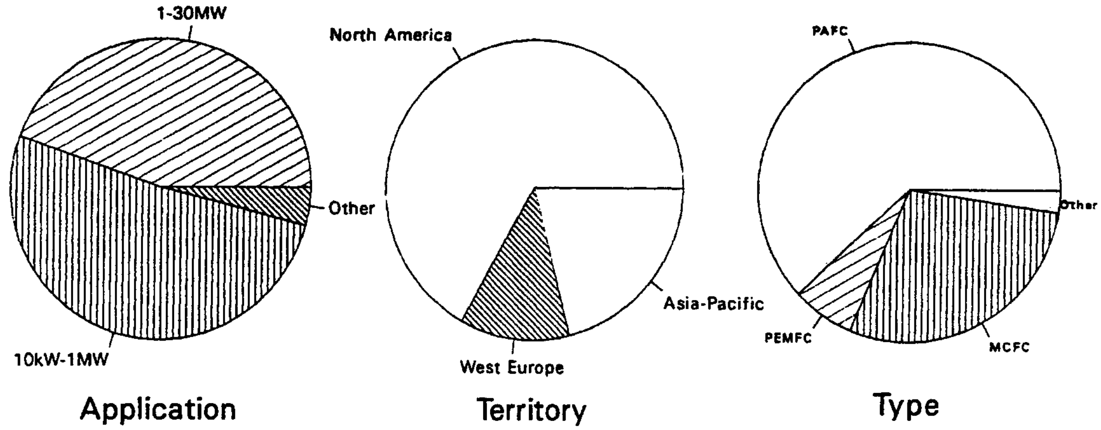


Figure B-1. Fuel Cell Markets in the 1990's
Source: EscoVale Consultancy Services Report No. 5010

B-2. MARKET FORECAST

The forecast in Table B-2 provides market figures at five-year intervals. Value estimates are also included, making assumptions regarding price trends. In practice, the value estimates are subject to even wider margins of error than the capacity figures. For example, the specific value of a truck fuel cell is in greater doubt than the truck's power rating.

Table B-2 shows the fuel cell market at less than 400MW in the year 2000, valued at close to $700M. This moves forward during the decade, to exceed 1,500MW by 2005, and 5,000MW by 2010 (with a value approaching $6 billion). Stationary applications still account for a large majority of the activity during this period, although the mobile sector has reached 1,000MW by 2010.

The final decade sees the total requirement increase to 20GW in 2005, and to more than 70GW in 2020, by which time the value is not far short of $30 billion. Mobile applications move to the forefront, and are credited with the majority of the capacity by 2015 (over 80 percent in 2020). Unit values are higher in the stationary plant sector. This contributes most of the total value, with mobile applications poised to move ahead at the end of the timescale.

It should be noted that these forecasts are extremely tentative and subject to many assumptions and provisions. The most striking feature however, is the high and sustained growth during the research period. Growth rates are abating towards the end of the timescale, although they are hardly pedestrian. Growth at this level is more a characteristic of a successful consumer product, than of industrial equipment. However, a point to note is that there are very few instances where fuel cells are creating new markets. For the most part, they are gaining a position in established business areas of considerable size. In this respect, the forecasts are not

spectacular. More than two decades after their commercial introduction, fuel cells are predicted to have gained shares approaching 5 percent in power plant and 1 percent in transportation.

	Year				
	2000	2005	2010	2015	2020
CAPACITY - MW & (%)					
Stationary	375 (99%)	1,450 (95%)	4,350 (79%)	8,650 (44%)	13,800 (19%)
Mobile	<5 (1%)	75 (5%)	1,150 (21%)	11,200 (56%)	57,000 (81%)
TOTAL (MW)	375	1,550	5,500	19,900	71,800
VALUE - $M & (%)					
Stationary	*675 (99%)*	*2,100 (97%)*	*5,300 (89%)*	*9,900 (70%)*	*14,600 (50%)*
Mobile	*5 (1%)*	*50 (3%)*	*625 (11%)*	*4,300 (30%)*	*14,500 (50%)*
TOTAL ($M)	*675*	*2,100*	*5,900*	*14,000*	*29,000*

Table B-2. Fuel Cell Market Forecast (2000-2020)
Source: EscoVale Consultancy Services Report No. 5010

Figure B-2 illustrates the market forecast for stationary and mobile applications. Confidence limits have not been assessed since attempts to do this for an emerging technology seldom do more than underline the hazards of forecasting.

The primary concern with the subject forecasting relates not so much to the scale of the opportunity, but more to the timing of market development. This is shown in Figure B-3, which indicates the effect of assuming that development timescales beyond 2000 are accelerated or delayed by 10 percent.

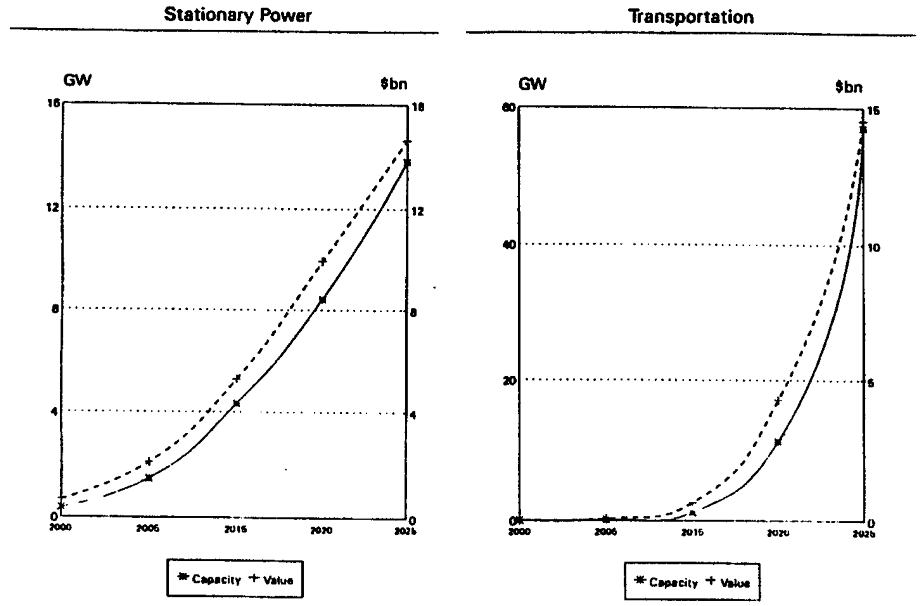


Figure B-2. Fuel Cell Forecasts by Capacity and Value
(Source: EscoVale Consultancy Services Report No. 5010)

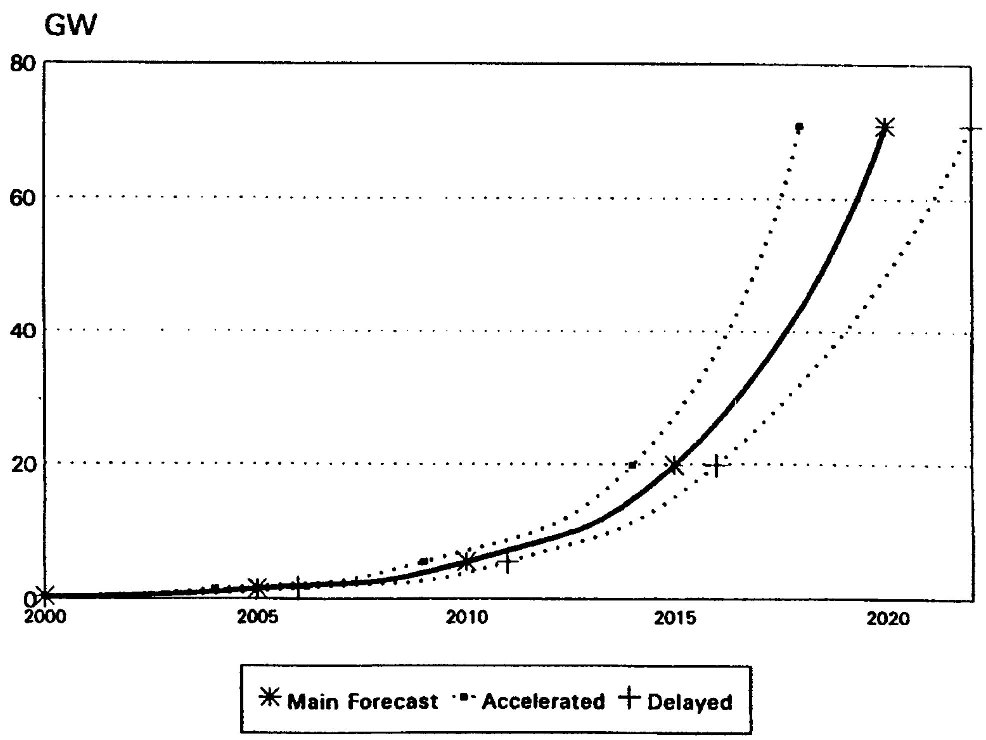


Figure B-3. Fuel Cell Market Sensitivity, 2000-2020
(Source: EscoVale Consultancy Services Report No. 5010)

B-3. APPLICATION FORECAST

Table B-3 shows the forecast of fuel cell market development by application. The columns at the right of the table indicate the approximate distribution by territory and fuel cell type. Note, the way in which this has been assessed may slightly overstate the contribution of the categories growing most rapidly at the end of the forecast period. Table B-4 shows a very tentative estimate of the value.

Application	Year					Territory				FC Type	
	2000 (MW)	2005 (MW)	2010 (MW)	2015 (MW)	2020 (MW)	North America (%)	West Europe (%)	Asia Pacific (%)	Other Regions (%)	Low Temp (%)	High Temp (%)
>30MW	...	50	175	525	1,300	35	24	30	11	10	90
1-30MW	225	1,100	3,450	6,700	10,200	48	31	15	7	16	84
10kW-1MW	150	275	525	950	1,550	37	25	31	8	46	54
<10kW	10	50	175	450	800	33	26	38	3	69	31
Stationary (MW)	375	1,450	4,350	8,650	13,800	46	29	19	7	22	78
Stationary ($M)	*(675)*	*(2,100)*	*(5,300)*	*(9,900)*	*(14,600)*					*(27)*	*(73)*
Rail/Marine	...	5	25	75	200	35	21	40	3	92	8
Comm Vhcls	<5	50	475	3,450	14,500	54	17	24	4	83	17
Cars	...	25	625	7,500	41,500	46	18	35	1	85	15
Other	...	<5	15	175	875	42	23	32	3	91	9
Mobile (MW)	<5	75	1,150	11,200	57,000	46	18	32	2	86	14
Mobile ($M)	*(5)*	*(50)*	*(625)*	*(4,300)*	*(14,500)*					*(84)*	*(16)*
TOTAL (MW)	375	1,550	5,500	19,900	71,000	47	21	28	[illegible]	68	32
TOTAL ($M)	*(675)*	*(2,100)*	*(5,900)*	*(14,000)*	*(29,000)*					*(48)*	*(52)*

Table B-3. Fuel Cell Market Forecast by Application (2000-2020)
(Source: EscoVale Consultancy Services Report No. 5010)

Despite the fact that market development commences later than that of some other sectors, the passenger car area is considered to be the leading fuel cell application in capacity terms over the research period, and is the dominant outlet by 2020 with almost 60 percent of the total. It ranks second to mid-range power plant in value, but is growing more rapidly at the end of the timescale.

Commercial vehicles rank third in terms of aggregate capacity and value. The sector share is rising strongly over the last decade, to overtake the 1-30 MW application, finishing with around 20 percent of the capacity (still well behind in value terms, at less than 15 percent).

Power generation in the 1 -30MW band is the leading outlet until about 2015, when the surge in automotive applications reduces its capacity share. This was standing at 60-70 percent from 2000-2010, slipping to around 35 percent in 2015 and 15 percent in 2020. The sector shows up still more strongly in value, where it is the leading market for the period as a whole, accounting for more than half the value until 2015 and still retaining one-third of the market in 2020.

Application	Year				
	2000 ($M)	2005 ($M)	2010 ($M)	2015 ($M)	2020 ($M)
>30MW	...	50	200	550	1,300
1-30MW	350	1,400	3,900	7,100	9,800
10kW-1MW	275	500	800	1,200	1,800
<10kW	50	150	450	1,000	1,700
Total Stationary	700	2,100	5,300	9,900	14,600
Rail/Marine	...	10	50	100	200
Comm Vehicles	...	30	250	1,300	3,800
Passenger Cars	...	20	300	2,800	10,200
Other	...	...	10	75	350
Total Mobile	...	50	650	4,300	14,500
TOTAL ($M)	700	2,100	5,900	14,000	29,000

Table B-4. Value Forecast by Application
(Source: EscoVale Consultancy Services Report No. 5010)

The other sectors, including the marine sector, are small by comparison. However, the sub-1 MW area has an important position initially, and is credited with almost 10 percent of the aggregate value across this period (about 40 percent initially, but reducing to under 25 percent by 2005, when the share attributed to higher power units is at its peak).

The market for units below 10 kW is significantly smaller in capacity terms, however the specific values here are high. It probably accounts for 6-7 percent of the aggregate value and is moving up towards the sub-1 MW sector by 2020.

B-4. TERRITORIAL FORECAST

The manner in which the market distribution is expected to evolve by region is shown in Table B-5. North America is allocated almost half of the fuel cell market over the research period, commencing at close to 60 percent and drifting down towards 45 percent by 2020.

Western Europe advances from about 15 percent to 25 percent in the first decade, before slipping back to a share of around 20 percent. Asia-Pacific exhibits the opposite trend, with an initial share of 25 percent, resulting partly from the assumption of strong introductory support in Japan. Some of the more active markets in the early 2000s are thought to have a larger constituency in Europe than Japan, with the Asia-Pacific share dipping to about 15 percent. This recovers to about 30 percent in the 2010s, mainly due to the altered structure of the fuel cell market, but also reflecting regional markets outside Japan. Other areas are not expected to represent major fuel cell markets, contributing about 3 percent of the total.

Region	Year				
	2000 MW & (%)	2005 MW &(%)	2010 MW & (%)	2015 MW & (%)	2020 MW & (%)
North America	225 (59%)	950 (61%)	3,000 (54%)	9,600 (49%)	32,500 (46%)
West Europe	50 (15%)	325 (21%)	1,400 (26%)	4,600 (23%)	14,600 (21%)
Asia-Pacific	100 (26%)	250 (16%)	950 (17%)	5,000 (25%)	21,400 (30%)
Other Regions	... ...	25 (1%)	150 (3%)	600 (3%)	2,400 (3%)
TOTAL (MW)	375	1,600	5,500	19,900	71,000

Table B-5. Fuel Cell Forecast by Region (2000-2020)
(Source: EscoVale Consultancy Services Report No. 5010)

B-5. STATIONARY POWER FORECAST

Table B-6 summarizes the forecast of market development by fuel cell type for stationary power applications (note that the sub-10kW sector includes small portable units and battery replacements). The estimates are presented as assessed, but are based on numerous assumptions, and thus it would be very surprising if there were not substantial modifications, resulting from information gathered during future work planned in this area.

For the research period as a whole, MCFCs are the leading category, accounting for over 40 percent of the capacity and around 35 percent of the value. By 2020, MCFCs are credited with about 5.5GW, worth around $5 billion. Its share of the stationary power sector increases initially and then slips back, with Solid Oxide Fuel Cells (SOFCs) moving into the top position.

SOFC, with a broader distribution amongst the various applications, ranks second on the basis of the present forecast, with about 35 percent of the overall capacity and value. This is a high growth area which is expected to lead the market by 2020 with over 5.5GW and $6 billion.

Phosphoric Acid Fuel Cells (PAFCs) are the market leader initially and take third place overall with about 15 percent of the total in the stationary power sector. Growth is at a comparatively slow pace, with the result that PAFCs are overtaken by MCFCs (by 2005) and SOFCs (by 2010). However, according to this forecast, the PAFC market increases throughout the period to 2020, to reach almost 1.5GW, still representing about 10 percent of the stationary power total at that time.

PEMFCs account for about 6 percent of the aggregate capacity (finishing at over 1GW, which is well ahead of some expectations as far as stationary applications are concerned). As is apparent from the application analysis in Table B-6, PEMFCs have a stronger position at lower

power ratings. This is reflected in a relatively high value share - about 10 percent overall, and finishing ahead of PAFCs.

FC Category	Year					Application			
	2000 (MW)	2005 (MW)	2010 (MW)	2015 (MW)	2020 (MW)	>30MW (%)	1-30MW (%)	10kW-1MW (%)	<10kW (%)
PAFC	175	350	900	1,300	1,400	5	73	22	...
AFC	<5	5	20	50	75	...	...	<5	>95
PEMFC	25	100	200	400	1,200	...	27	36	37
DMFC	...	<5	25	50	100	...	...	<5	>95
Low Temp (MW)	200	450	1,100	1,800	2,700	3	56	25	16
Low Temp ($M)	*(350)*	*(700)*	*(1,600)*	*(2,500)*	*(3,600)*	*(2)*	*(43)*	*(26)*	*(29)*
SOFC	50	350	1,300	3,100	5,700	7	75	15	4
MCFC	125	675	1,900	3,800	5,500	10	87	3	...
High Temp (MW)	150	1,000	3,200	6,800	11,100	8	81	8	2
High Temp ($M)	*(350)*	*(1,400)*	*(3,700)*	*(7,400)*	*(11,000)*	*(8)*	*(78)*	*(10)*	*(4)*
TOTAL (MW)	375	1,500	4,300	8,600	13,800	7	76	12	5
TOTAL ($M)	*(700)*	*(2,100)*	*(5,300)*	*(9,900)*	*(14,600)*	*(6)*	*(69)*	*(14)*	*(10)*

Table B-6. Fuel Cell Market Forecast – Stationary Power
(Source: EscoVale Consultancy Services Report No. 5010)

B-6. TRANSPORTATION FORECAST

The forecast for transportation, presented in Table B-7, is subject to still more caveats in terms of the assumptions underlying the analyses. This is the area where there is greatest contention with regard to fuel cell technologies and their timing.

FC Category	Year					Application			
	2000 (MW)	2005 (MW)	2010 (MW)	2015 (MW)	2020 (MW)	Rail/Marine (%)	Comm Vcls (%)	Cars (%)	Other (%)
PAFC	<5	20	125	550	800	9	91	...	...
AFC	...	5	75	750	3,600	...	42	56	1
PEMFC	<5	50	750	6,400	27,800	...	24	73	2
DMFC	...	<5	150	2,400	15,600	...	19	79	2
Low Temp (MW)	<5	75	1,100	10,100	48,000	1	26	72	2
Low Temp ($M)	*(2.5)*	*(50)*	*(600)*	*(3,700)*	*(11,800)*	*(2)*	*(27)*	*(68)*	*(3)*
SOFC	...	...	50	1,100	9,200	...	32	67	1
MCFC	...	...	...	...	...	...	...	...	...
High Temp (MW)	...	...	50	1,100	9,200	...	32	67	1
High Temp ($M)	...	...	*(50)*	*(550)*	*(2,700)*	*(1)*	*(30)*	*(68)*	*(1)*
TOTAL (MW)	<5	75	1,200	11,200	57,000	[illegible]	27	71	2
TOTAL ($M)	*(<50)*	*(50)*	*(650)*	*(4,300)*	*(14,500)*	*(2)*	*(26)*	*(69)*	*(2)*

Table B-7. Fuel Cell Market Forecast – Transportation
(Source: EscoVale Consultancy Services Report No. 5010)

That said, there is wide support for PEMFCs as the market leader in this sector. PEMFCs are credited with about 50 percent of the aggregate capacity and 45 percent of the value over the research period, retaining the leading position throughout. The forecast for 2020 is approximately 28GW and over $6 billion. The sheer size of the automotive sector is such that this exceeds the capacity of all stationary power fuel cells (despite the greater fuel cell penetration in the power plant market).

The assumption that Direct Methanol Fuel Cells (DMFCs) will be a practical proposition, making a contribution as early as 2010, results in a comfortable second place, with roughly 25 percent of the transportation business. This equates to about 15 GW and $4 billion by 2020. While there are strong advocates for DMFC, most would agree that this is a particularly speculative area.

Much the same can be said for planar SOFCs, credited with some 15 percent of the aggregate transportation market, to rank third overall. In this case, reservations about the technical problems which remain to be overcome are compounded by doubts surrounding the applicability of high temperature fuel cells in an automotive environment. Nevertheless, some of those most actively involved in the industry see it as a very strong contender, and may be the market leader by 2020.

B-7. REFERENCES

(December 1998). Fuel Cells: Applications and Opportunities. EscoVale Consultancy Services, Report No. 5010.

(December 1998). Fuel Cells: The Source Book. EscoVale Consultancy Services, Report No. 3400.

APPENDIX C.
POTENTIAL DEMAND BY MARKET SEGMENT AND ECONOMIC GROWTH

Demand for fuel cells will be bounded by the demand for new ships built. Therefore, the first objective of this section is to forecast the number of vessels that are likely to be built over the forecast period.

C-1. KEY MARKET SEGMENTS

Key market segments were identified in Table C-1 which is reproduced below in its entirety for convenience. Table C-1 lists the major ship types that represent historically important application categories. These categories comprise the major market segments treated in this study. Table C-1 also shows the numbers of vessels built by decade from 1960 through 1998. Ship categories are shown in descending order, based on quantity of vessels constructed per decade. A striking example of the market breadth is that during the decade from 1960 through 1969, 4,346 fishing vessels were built, while 2,603 general cargo vessels were built during the same period.

Table C-1. Types of Vessels That Comprise Study Market Segments

SHIP TYPE	YEAR BUILT 1960-1969	1970-1979	1980-1989	1990-1998	Total	VESSELS ON ORDER Jan. 1999
Fishing Vessels	4346	7906	7081	3283	22616	236
General Cargo	2603	5431	4557	3098	15689	474
Tugs	1408	2635	1856	1957	7856	288
Oil Tankers	851	2420	1810	1623	6704	338
Bulk Carrier	246	1848	2110	1654	5858	292
Passenger Vessels	925	1383	1436	1427	5171	187
Offshore Vessels	249	976	1149	247	2621	70
Other Tankers	158	518	904	911	2491	163
Container	32	421	587	1356	2396	232
Hoppers/Dredgers	243	461	581	191	1476	16
Refrigerated Cargo	161	400	537	313	1411	33
RO-RO/Vehicle	69	516	531	280	1396	119
LPG/LNG Tanker	82	300	302	377	1061	70
Total	11,373	25,215	23,441	16,717	76,746	2,518

Three important results of this study are reflected in Table C-1. First, the table shows that of the 87,643 total commercial ships captured in the Lloyds database, 81,378 individual vessels, or 93 percent of the commercial market, are captured in the thirteen categories listed. Therefore, it can be concluded with confidence that analysis of these segments yields results that apply to a large fraction of the world commercial market. Second, a clear pattern of build rates emerges over the last four decades. Inspection of Table C-1 shows that, in general, rank ordering of major market segments did not change in terms of number of vessels built since 1960. Those segments that were dominant in the 1960's tend to still be dominant in the 1990's. Exceptions to this trend are container vessels, hoppers/dredgers, refrigerated cargo vessels, RO-RO/vehicle vessels and LPG/LNG tankers. In the case of container vessels and LPG/LNG tankers, the data show an emerging application that is likely to continue in the future. Hoppers/dredgers, and refrigerated cargo remain important segments but are not growing at the same rate as container vessels.

The third result follows directly from the second. Table C-1 suggests that the commercial vessel market has been remarkably stable over the last forty years. The "On Order" column shown on the right of Table C-1 lists the vessels that are on order as of January, 1999. With the exception of container vessels, RO-RO/vehicle vessels and offshore vessels, current orders are generally consistent with numbers of vessels in the existing commercial fleet. Although the number of RO-RO vessel builds fell off during the decade of the 1990's, construction of new vessels in this market segment tends to be increasing once again. Stability of trends for these segments give confidence that forecasts of build rates for vessels in these categories may remain somewhat stable through the year 2015.

While specific market segments will grow at different rates, overall vessel production will be consistent with global economic activity. Variations among market segments are expected to vary somewhat around mean global growth. Global economic activity and projections of market segment demand for commercial vessels are developed in this section.

C-2. GLOBAL ECONOMIC GROWTH

Growth in market segments is expected to be bounded by the global economic activity that drives imports and exports, which in turn drive demand for use of ships that comprise major market segments shown in Table C-1. Compound annual growth rates (CAGR) in the numbers of vessels for these categories are expected to be consistent with broader global economic indicators because they will tend to reflect trends in international commerce. Growth rates in global economies are expected to vary considerably from each other, but overall variation is expected to be relatively small.

C-2.1. Rates of Growth For Developed Economies

Rates of growth for 16 selected developed economies are shown in Table C-2. The average annual growth rate in GDP over the last 12 months for all 16 developed countries is 2.35 percent, during a period when these economies are experiencing moderately strong, stable performance. Excluding Japan, average annual growth rate for these economies is 2.75 percent in the same period. With or without Japan, growth is small and positive. Although Japan is

currently experiencing some recessionary pressures, that country has a history of positive economic performance and growth.

Table C-2. Annual Growth Rates For Developed Economies

ECONOMY	% ANNUAL GROWTH in GDP OVER LAST YEAR
Australia	+ 4.7
Austria	+ 2.7
Belgium	+ 1.9
Britain	+ 1.3
Canada	+ 2.8
Denmark	+ 3.4
France	+ 2.8
Germany	+ 2.6
Italy	+ 1.2
Japan	- 3.6
Netherlands	+ 3.1
Spain	+ 3.6
Sweden	+ 3.2
Switzerland	+ 1.2
United States	+ 4.3
Euro-11	+ 2.4

Source: The Economist. March 13th – 19th 1999

Over the forecast period, there may be a degree of uncertainty in the ability of developed economies to sustain overall growth rates consistent with performance over the last 12 months. On the other hand, the recent economic downturn in Japan may also not continue over the forecast period; that country may succeed in improving its growth in GDP. Therefore, it appears reasonable to expect that GDP CAGR for this group of countries will vary in the future somewhere between the relatively poor current performance of Japan and the relatively strong performance of the balance of these economies. For the purposes of this study, economic CAGRs of minus 3.6 percent and plus 2.75 percent are considered reasonable approximations of expectations for economic growth of the world's economically mature economies.

C-2.2. Rates of Growth for Selected Emerging Economies

For the 25 emerging economies shown in Table C-3, annual growth in gross domestic product over the past twelve months has averaged –0.90 percent.

Table C-3. Annual Growth In GDP For Selected Emerging Economies

ECONOMY	% ANNUAL GROWTH in GDP OVER LAST YEAR
China	+ 9.6
Hong Kong	- 7.1
India	+ 5.0 (1997)
Indonesia	- 13.9
Malaysia	- 8.6
Philippines	- 1.9
Singapore	- 0.8
South Korea	- 6.8
Taiwan	+ 3.7
Thailand	- 6.5 (1998)
Argentina	- 0.5
Brazil	- 1.9
Chile	+ 2.7
Colombia	- 5.0
Mexico	+ 2.6
Venezuela	- 8.2
Egypt	+ 5.7 (1998)
Greece	+ 3.5
Israel	+ 1.8
South Africa	- 0.5
Turkey	+ 1.6
Czech Republic	- 2.9
Hungary	+ 5.6
Poland	+ 5.0
Russia	- 4.6

Source: The Economist. March 13th – 19th 1999

The variation in growth rates for emerging economies is considerably greater than that shown for mature economies, which is to be expected because the GDP of these nations are smaller, and their performance is more vulnerable to domestic and international economic pressures. On average, the growth rates of this group of 25 economies are in the low single digits, with a small negative cumulative rate. Also, on average, these economies have been experiencing a degree of short term difficulty managing economic growth. This difficulty is particularly true of the Asian, and to some extent the Latin American economies. Since these nations have had a degree of recent difficulty, it may be reasonable to expect that they will experience modest economic recovery through the forecast period. Since current GDP growth is

a small negative rate, it may be reasonable to expect that over the forecast period, CAGR in developing economies' GDP will vary from slightly negative to slightly positive.

C-2.3. Economic Growth Rates and the Growth of Commercial Vessels

These growth rates, whether positive or negative, are expected to remain in the low single digits over the forecast period. For the purposes of this study, economic CAGRs of minus 3.6 percent and plus 2.75 percent are considered reasonable approximations of expectations for economic growth of the world's economically mature economies.

In any case, overall growth of commercial vessels will track the overall growth rate of the global economies. It appears likely that the global rate of growth may be a small negative number or slightly positive. In the event of negative global growth in GDP, the growth rate in vessels may be zero for some market segments because economies will either utilize existing capacity, or will scrap excess ships. If global economic growth is positive, vessel growth rates will be small. For the purposes of this study, growth rates in vessel production will be assigned a value of zero if the market segment is mature. That is, historical rates of vessel construction will be assumed to be flat over the forecast period. For selected market segments where recent historical growth has been demonstrated, vessel production growth rates will be assigned small positive numbers, consistent with the GDP growth rates.

C-3. GROWTH IN COMMERCIAL VESSEL MARKET SEGMENTS

Typical growth rates of vessel construction, and the levels of vessel production derived from historical levels and projected growth rates are shown in Figures C-1 through C-3. These figures are histograms that represent historical vessel build rates since the 1960's for three typical market segments. The histograms shown in Appendix H form the basis for projections of vessel build frequency over the forecast period, and are discussed in this section.

Referring to Appendix H, fishing vessels, general cargo, oil tankers, offshore vessels, hoppers/dredgers and refrigerated cargo represent market segments that are large but for which no net growth is expected over the forecast period. Vessel counts in these market segments are expected to be very consistent with historical quantities of ships. An example of a flat growth market segment is shown in Figure C-1.

By comparison, tugboats, bulk carriers, RO-RO/Vehicle vessels and yachts are expected to experience moderate growth, consistent with historical trends. An example of a moderate growth segment is shown in Figure C-2.

Passenger vessels, LPG/LNG tankers, container vessels and other tankers are expected to experience strong growth. The market segment "other tankers" in this study includes chemical tankers, which have recently been experiencing sliding usage. But the overall demand for this market segment appears to be strong, even with no turnaround in chemical tanker demand. An example of a strong growth segment is shown in Figure C-3.

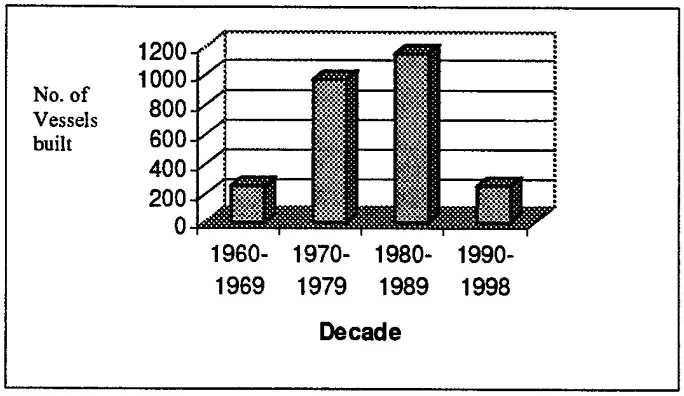


Figure C-1. Historical Build Rates For Offshore Vessels Since 1960

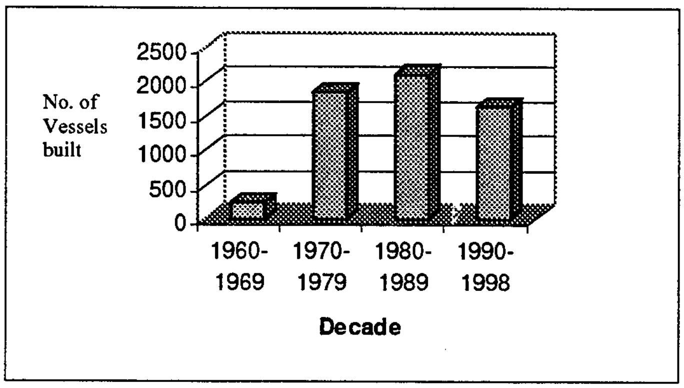


Figure C-2. Historical Build Rates For Bulk Carriers Since 1960

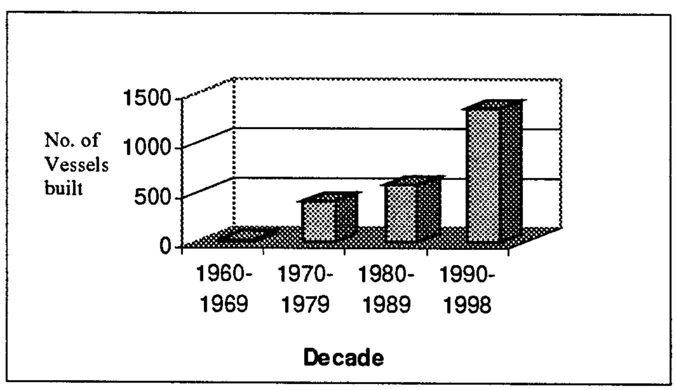


Figure C-3. Historical Build Rates For Container Ships Since 1960

Compound annual growth rates are shown for each of the study market segments in Table C-4. Annual demand will push growth to levels substantially higher than those shown in Table C-4. In addition, periodic fluctuations in quantity demanded by vessel type will fluctuate through the year 2015. The project CAGRs are averages, which will be reflected in integrated into five-year aggregates for the purposes of building forecasts for fuel cell maximum markets by segment.

Table C-4. Compound Annual Growth Rate By Market Segment

MARKET SEGMENT	PROJECTED GROWTH	AVERAGE CAGR (%)
Fishing vessels	None	0.0
General cargo	None	0.0
Tugs	Moderate	1.5
Oil Tankers	None	0.0
Bulk carriers	Moderate	1.5
Passenger vessels	Strong	3.0
Offshore vessels	None	0.0
Other tankers	Strong	3.0
Container ships	Strong	3.0
Hoppers/Dredgers	None	0.0
Refrigerated cargo ships	None	0.0
RO-RO/Vehicle vessels	Moderate	1.5
LPG/LNG tankers	Strong	3.0

Applying the CAGR for each market segment to historical build rates from the Lloyds database yields the expected growth in vessels shown in Table C-5. The approach is to extrapolate a reasonable linear forecast, using the rates shown in Table C-4. Vessel counts in the out-years projected by linear forecasts are sensitive to the starting vessel count to which the CAGR is applied. Therefore, care was taken to use reasonable starting points for vessel counts.

For segments that are projected to grow at zero percent, the average build rate per year over the period 1960 and 1998 is used as a base from which vessel count is extrapolated. For growing segments, CAGR is applied to the average number of vessels built during the period 1980 through 1998, with the exception of container ships. Container ships CAGR is applied to the average number of ships per year from 1990 through 1998 because the market segment has experienced strong recent growth. These growing segments average shorter, more recent time periods to avoid excessive weighting of data from early years that do not reflect segment usage. Using this methodology yields the vessel count projections shown in Table C-5.

Table C-5. Projected Vessels Built Through The Forecast Period, By Market Segment

MARKET SEGMENT	No. of Years Used to Calculate Average	Average Number Ships Built/Year Prior to Forecast Period	Projected CAGR Through Forecast Period (growth over average prior to forecast)	Forecast Vessels Built Between 01 and 05 (5 years)	Forecast Vessels Built Between 06 and 10 (5 years)	Forecast Vessels Built Between 11 and 15 (5 years)
Fishing Vessels	39	605.38	0.00 %	4,238	3,027	3,027
General Cargo	39	434.05	0.00 %	3,038	2,170	2,170
Tugs	19	200.68	1.50 %	1,492	1,165	1,255
Oil Tankers	39	179.44	0.00 %	1,256	897	897
Bulk Carriers	19	198.11	1.50 %	1,472	1,150	1,239
Passenger Vessels	19	150.68	3.00 %	1,189	1,013	1,175
Offshore Vessels	39	68.36	0.00 %	479	342	342
Other Tankers	19	95.53	3.00 %	754	642	745
Container Ships	9	150.67	3.00 %	1,189	1,013	1,175
Hoppers/Dredgers	39	41.15	0.00 %	288	206	206
Refrg. Cargo Ships	39	37.13	0.00 %	260	186	186
RO-RO/Veh. Ships	19	42.68	1.50 %	317	248	267
LPG/LNG Tankers	19	35.74	3.00 %	282	240	279

C-4. EXTRAPOLATED TRENDS FOR MARINE MARKET SEGMENTS

Table C-5 reflects segment forecasts that comprise seven years in the first forecast period (calendar years 1999 through 2005). Each of the additional two forecast periods comprises five year increments. It is important to note that the histograms in this report show projections for each market segment based on five year increments, starting in calendar year 2001. The actual analysis also subsumes calendar years 1999 and 2000. The reason that the histograms all show projections in five year intervals is to avoid possible confusion if quantities of vessels in the first period appear larger, which would be the case if the first forecast period subsumed seven years instead of five.

The projected vessel counts shown in Table C-5 are generally consistent with historical build rates. Container ships represent the single largest anomaly, due to the recent expansion of that segment into the marketplace.

Over the forecast period fishing vessels remain the single largest market segment. Although the growth rate is flat, average annual production in 2015 is over 600 vessels per year, compared with about 365 per year in the 1990's. The relatively aggressive net forecast is consistent with historical build rates. But fishing vessels on order number only 236 in January 1999. If the downward trend in construction since the 1970's does not reverse, the fishing vessel segment will be overestimated by the method chosen.

Annual production of general cargo vessels is consistent with both historical trends and vessels on order. Tugboats are projected to grow at a CAGR of 1.5 percent, resulting in annual production in the out years of over 250 vessels per year. In January 1999, there are 288 tugboats on order, which indicates that out year forecasts are not aggressive. The January 1999 on-order count for oil tankers is 338, almost double the annual projected demand for the 2011 to 2015 annual forecast. The oil tanker forecast therefore also appears to be conservative. The out year forecast for bulk carriers is somewhat more than the 184 vessels built per year during the 1990's, but less than the 292 vessels currently on order. Refrigerated cargo vessels and LPG/LNG tanker forecasts through the year 2015 are consistent with build rates during the 1990's.

Bulk carriers, passenger vessels, offshore vessels, other tankers, containers and hoppers/dredgers all reflect projections that are about 50 percent greater by the year 2015 than the average annual build rates for the decade of the 1990's. These are the segments that are expected to grow the most rapidly. Even with modest CAGRs of 1.50 percent to 3.00 percent, these segments achieve substantial vessel counts.

In the cases of bulk carriers, offshore vessels, other tankers and container ships, the January 1999 orders already meet or exceed the out year forecast rates, which might otherwise be interpreted to be aggressive. Although it is very difficult to predict with accuracy the annual fluctuations in construction rates for these market segments, the forecasts appear to be reasonable and consistent with recent historical rates and current trends.

C-5. POTENTIAL DEMAND FOR POWER UNITS BY MARKET SEGMENT

C-5.1. Standard Complement Factor

In Paragraph C-4 forecasts were developed for vessels that comprise major commercial markets. In this paragraph, forecasts for power units and SSGs are developed. Using the commercial vessel database, average numbers of propulsion units and SSG units were derived for each market segment using large numbers of vessels in each segment. These numbers of power units were segregated by power size, resulting in average power units that apply to a "standard" ship in each market segment. The statistical mean number of power units per vessel is referred to as a Standard Complement Factor (SCF). The SCF is the average number of power units of a certain size (kW or MW) that is found in each market segment based on analysis of statistically large numbers of ships. The SCF is a factor that can be multiplied by the number of future ships of a certain market segment to project future requirements for power units of a certain size. Because the SCF is a factor, it is not an integer and does not represent the actual number of power units of a given size that would actually be deployed on a specific vessel.

For example, 2,621 fishing vessels were analyzed to identify both propulsion and SSG power requirements. Only vessels in the database for which it was certain that both propulsion and SSG power plant data had been recorded were included for this part of the analysis. With 2,621 vessels in the sample population, confidence was gained that the resultant SCFs would apply to the average vessel. Results for fishing vessels are shown in Tables C-6 and C-7.

Table C-6. Standard Complement Factors For Fishing Vessels

MW RANGE	VESSELS	PROPULSION UNITS	SCF
< 2	2,621	2,318	0.88
2 – 4	2,621	192	0.07
4 – 6	2,621	75	0.03
6 – 8	2,621	27	0.01
8 – 10	2,621	4	0.00
10 – 20	2,621	5	0.00
20 – 30	2,621	0	0.00
30 – 40	2,621	0	0.00
40 – 50	2,621	0	0.00
> 50	2,621	0	0.00

Table C-7. SSG Standard Complement Factors For Fishing Vessels

kW RANGE	VESSELS	SSGs	SCF
< 500	2,621	2,303	0.88
501 – 1500	2,621	351	0.13
1501 – 2500	2,621	110	0.04
2501 – 3500	2,621	20	0.01
> 3501	2,621	0	0.00

Totaling the numbers in the column titled "Propulsion units" yields 2,621, the total number of fishing vessels. Table C-6 shows that most propulsion units on fishing vessels are rated at less than 2 megawatts. Since 2,318 of the total 2,621 vessels are powered by units of less than 2 megawatts, the fraction of the total population that is powered by propulsion units of less than 2 megawatts can be calculated by the formula:

$$\text{SCF} = \text{Propulsion Units/Vessels, or} \qquad \text{Equation (C1)}$$

$$\text{SCF} = 2318/2621 = 0.88$$

In other words, 88 percent of fishing vessels are equipped with power plants with a rating of less than 2 megawatts. SCF values are derived using only ships constructed in the decade of the 1990's, which reflects the most modern use of propulsion power units for the market segment. This factor can be multiplied by vessel counts in the future to project a realistic forecast of the numbers of propulsion units per vessel of that size, assuming that propulsion requirements do not change substantially over the forecast period. SCFs for power plants greater than eight MW show SCF values of 0.00. While Table C-6 shows that nine fishing vessels have

propulsion units of eight to 20 MW, these are statistically insignificant out of a population of 2,621 vessels. The methodology will not forecast any power plant demand in the future for propulsion systems in these size ranges because the SCF is 0.00. While this may not be true in practice, exclusion of these outliers is considered appropriate because statistically they represent very limited market demand for this segment.

Similarly, SCF values can be developed for ship set generators. An example, also using fishing vessel data for the 1990's is shown in Table C-7. Again, SSG data are segregated by size based on power rating. The units of analysis for SSGs are in multiples of 500 kW or 1000 kW across all market segments as shown in Table C-7.

Inspection of Tables C-6 and C-7 show that 88 percent of fishing vessels have primary propulsion power units with ratings of less than 2 megawatts and SSG units with power ratings less than 500 kilowatts. This method was used for all market segments. Factors for each market segment are shown in the following paragraphs.

C-5.2. Standard Complement Factor Estimates For Propulsion

The procedure outlined above for fishing vessel propulsion SCF calculation is shown for all market segments in Table C-8. With the exceptions of oil tankers, bulk carriers, offshore vessels, container ships, refrigerated cargo ships, RO-RO vessels and some LPG/LNG tankers, most market segments utilize propulsion power plants that are rated at 10 MW or less.

Table C-8. SCF For Main Propulsion By Market Segment

MARKET SEGMENT	<2 MW	2-4 MW	4-6 MW	6-8 MW	8-10 MW	10-20 MW	20–30 MW	30-40 MW	40-50 MW	>50 MW
Fishing Vessels	0.88	0.07	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00
General Cargo	0.66	0.21	0.07	0.03	0.02	0.01	0.00	0.00	0.00	0.00
Tugs	0.53	0.43	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oil Tankers	0.37	0.16	0.03	0.06	0.07	0.23	0.08	0.00	0.00	0.00
Bulk Carriers	0.04	0.05	0.19	0.29	0.22	0.21	0.00	0.00	0.00	0.00
Passenger Vessels	0.37	0.25	0.11	0.03	0.03	0.10	0.07	0.02	0.01	0.01
Offshore Vessels	0.13	0.30	0.27	0.07	0.07	0.15	0.01	0.00	0.00	0.00
Other Tankers	0.43	0.28	0.09	0.10	0.07	0.03	0.00	0.00	0.00	0.00
Container Ships	0.02	0.08	0.08	0.09	0.12	0.31	0.11	0.10	0.05	0.03
Hopper/Dredgers	0.71	0.14	0.05	0.03	0.02	0.03	0.02	0.00	0.00	0.00
Refr'g Cargo Ships	0.09	0.16	0.22	0.16	0.15	0.22	0.00	0.00	0.00	0.00
RO-RO/Veh. Ships	0.05	0.17	0.19	0.09	0.14	0.33	0.02	0.00	0.00	0.00
LPG/LNG Tankers	0.25	0.37	0.10	0.02	0.08	0.12	0.05	0.01	0.00	0.00

C-5.3. Standard Complement Factor Estimates for Ship Service Generators

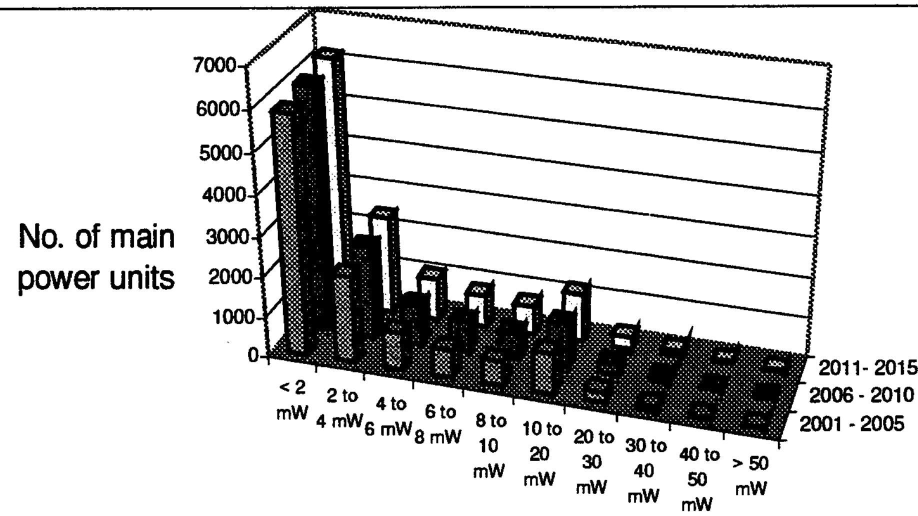
Distribution of SSG SCF factors for all market segments is shown in Table C-9. Virtually all the demand for SSG falls below 3500 kW. With the exception of offshore vessels

and container ships, most demand falls below 1500 kW. Table C-9 does not imply that 114 percent of bulk carriers require SSG power units rated at less than 500 kW, rather, SCF factors greater than 1.00 indicate that on average more than one SSG is required per vessel in the market segment at that power rating.

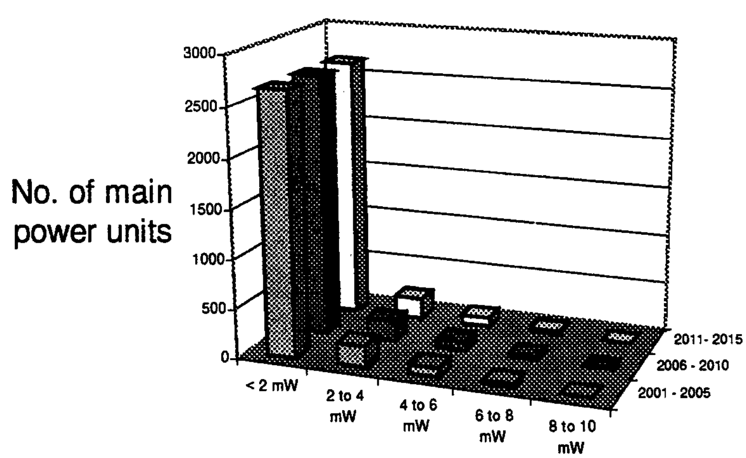
Table C-9. SCF For SSG by Market Segment

MARKET SEGMENT	< 500 kW	501-1500 kW	1501-2500 kW	2501-3500 kW	> 3501 kW
Fishing vessels	0.88	0.13	0.04	0.01	0.00
General cargo	1.03	0.21	0.00	0.00	0.00
Tugs	0.05	0.00	0.00	0.00	0.00
Oil Tankers	0.75	1.12	0.01	0.01	0.00
Bulk carriers	1.14	0.77	0.01	0.00	0.00
Passenger vessels	0.81	0.38	0.11	0.03	0.03
Offshore vessels	1.26	0.27	0.51	0.01	0.02
Other tankers	0.84	0.73	0.01	0.00	0.00
Container ships	0.38	1.57	0.39	0.06	0.02
Hoppers/Dredgers	1.01	0.22	0.04	0.02	0.05
Refr'g cargo ships	1.03	1.37	0.16	0.01	0.00
RO-RO/Veh. ships	0.81	1.43	0.06	0.00	0.00
LPG/LNG tankers	0.89	0.96	0.10	0.16	0.00

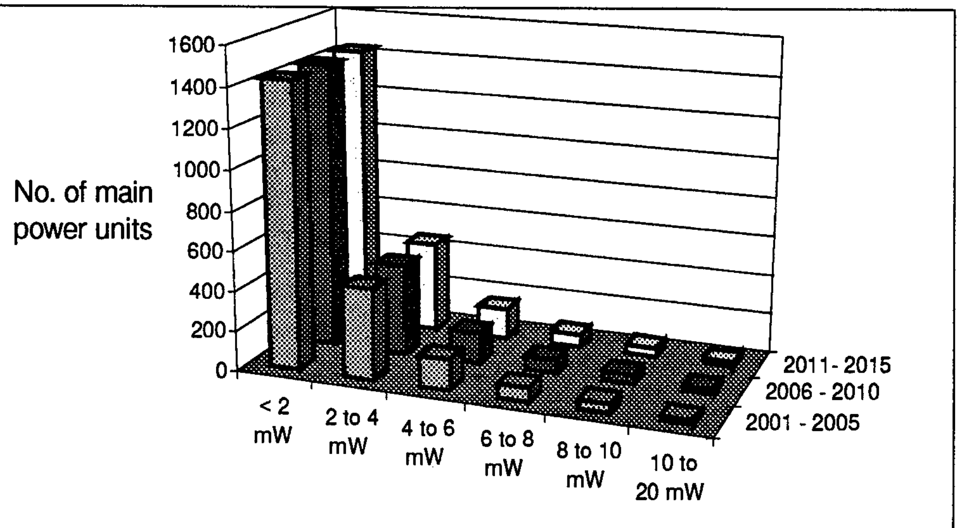
APPENDIX D.
MAIN POWER UNIT FORECAST FIGURES



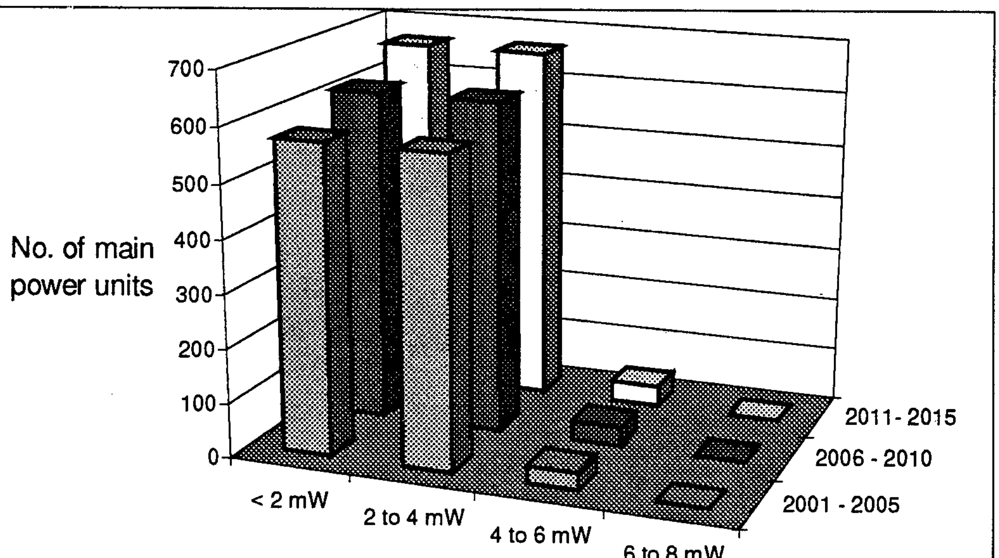
Main Power Unit Forecast -- ALL VESSEL TYPES



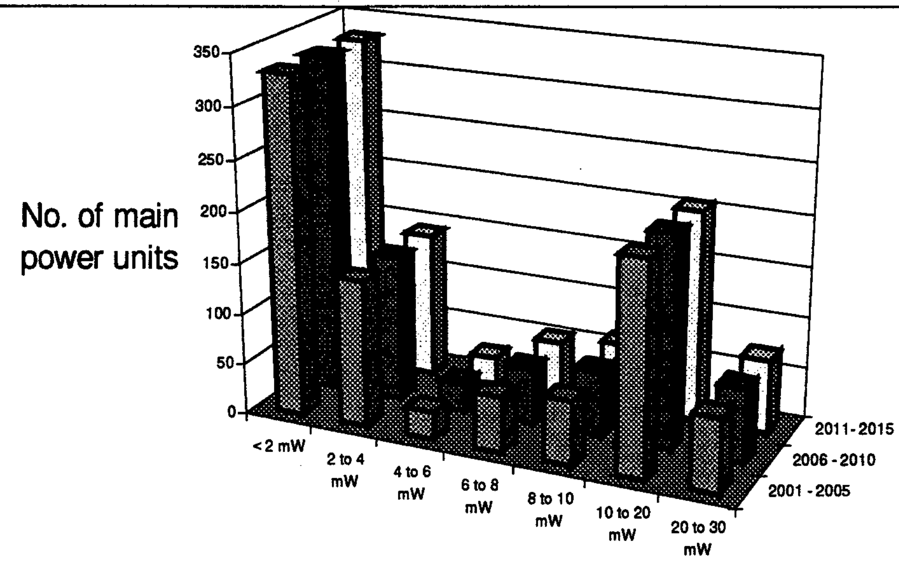
Main Power Unit Forecast for Fishing Vessels



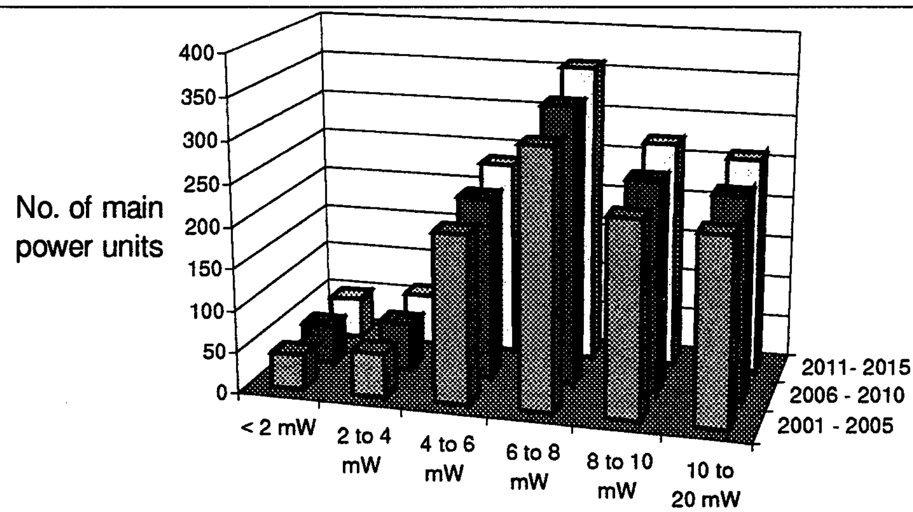
Main Power Unit Forecast for General Cargo Vessels



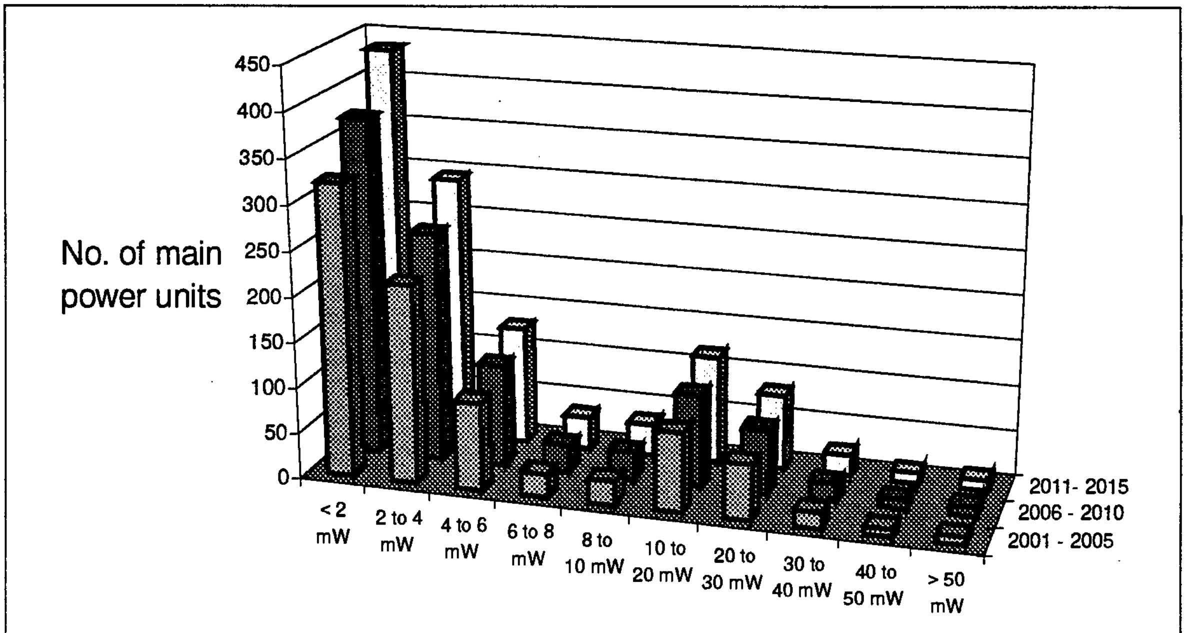
Main Power Unit Forecast for Tugs



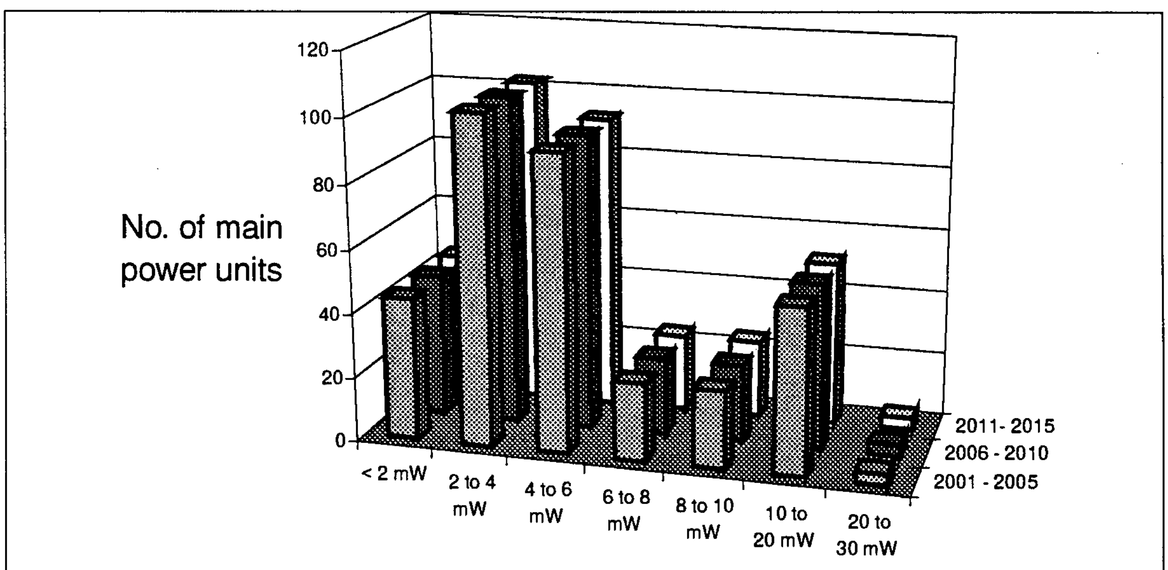
Main Power Unit Forecast for Oil Tankers



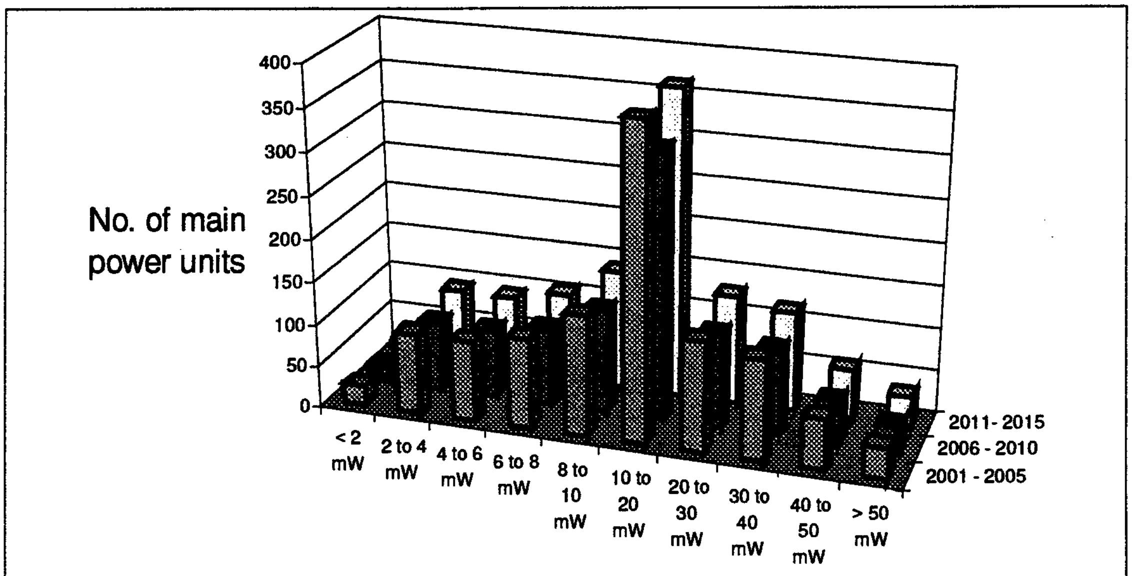
Main Power Unit Forecast for Bulk Carrier Vessels



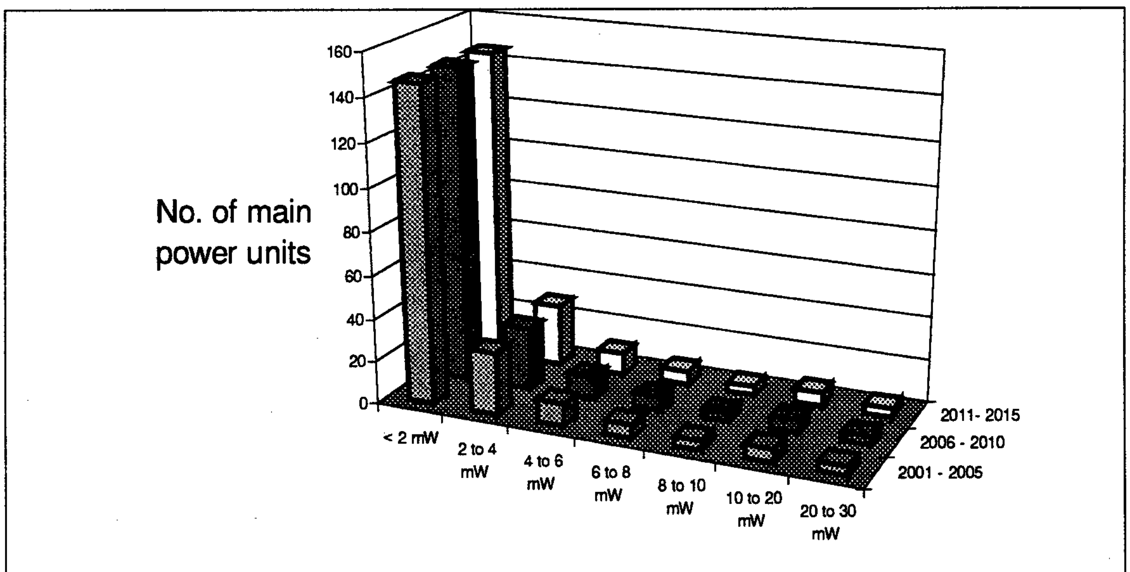
Main Power Unit Forecast for Passenger Vessels



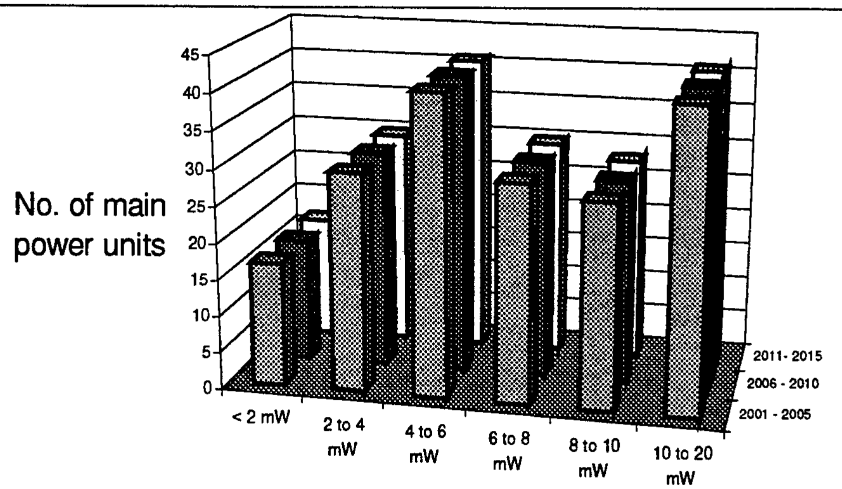
Main Power Unit Forecast for Offshore Vessels



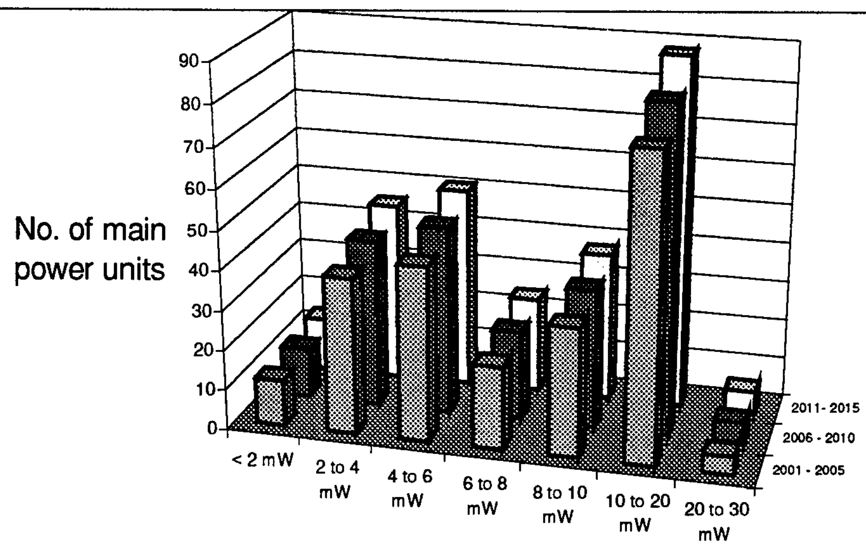
Main Power Unit Forecast for Container Vessels



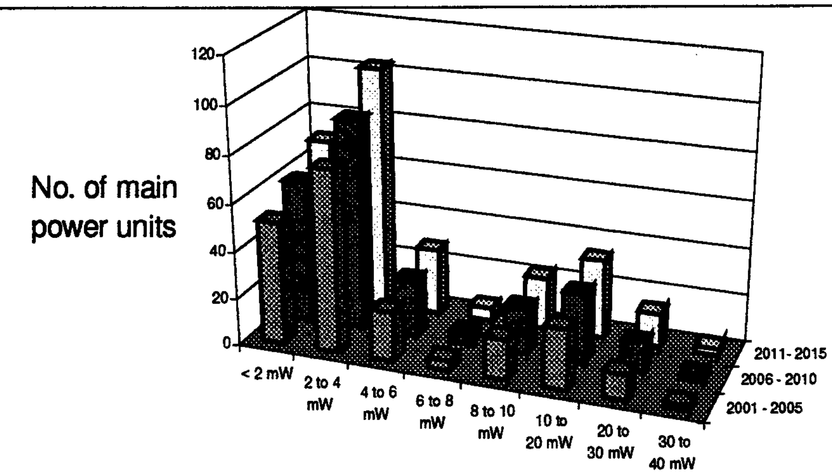
Main Power Unit Forecast for Hopper/Dredger Vessels



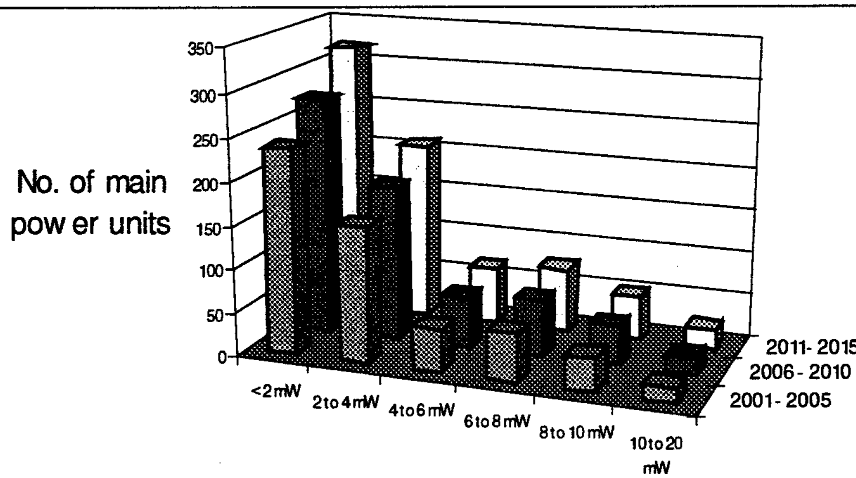
Main Power Unit Forecast for Refrigerator Vessels



Main Power Unit Forecast for RO-RO Vessels



Main Power Unit Forecast forLPG/LNG Vessels



Main Power Unit Forecast for Other Tankers

[This page intentionally left blank.]

APPENDIX E.
MAIN POWER UNIT FORECAST DATA

< 2 MW

Market Segment	2001 - 2005	2006 - 2010	2011- 2015
Fishing Vessels	2,663.69	2,663.69	2,663.69
General Cargo	1,432.37	1,432.37	1,432.37
Tugs	573.04	617.33	665.04
Oil Tankers	331.96	331.96	331.96
Bulk Carriers	42.69	45.99	49.55
Passenger Vessels	323.45	374.97	434.69
Offshore Vessels	44.43	44.43	44.43
Other Tankers	238.30	276.26	320.26
Container Ships	17.48	20.27	23.49
Hoppers/Dredgers	146.10	146.10	146.10
Refrg. Cargo Ships	16.71	16.71	16.71
RO-RO/Veh. Ships	11.50	12.39	13.34
LPG/LNG Tankers	51.83	60.09	69.66
Subtotal	**5,894**	**6,043**	**6,211**

2 to 4 MW

Market Segment	2001 - 2005	2006 - 2010	2011- 2015
Fishing Vessels	211.88	211.88	211.88
General Cargo	455.75	455.75	455.75
Tugs	573.04	617.33	665.04
Oil Tankers	143.55	143.55	143.55
Bulk Carriers	53.37	57.49	61.93
Passenger Vessels	218.55	253.35	293.71
Offshore Vessels	102.54	102.54	102.54
Other Tankers	155.17	179.89	208.54
Container Ships	69.93	81.06	93.98
Hoppers/Dredgers	28.81	28.81	28.81
Refrg. Cargo Ships	29.70	29.70	29.70
RO-RO/Veh. Ships	39.09	42.12	45.37
LPG/LNG Tankers	76.71	88.93	103.09
Subtotal	**2,158**	**2,292**	**2,444**

4 to 6 MW

Market Segment	2001 - 2005	2006 - 2010	2011- 2015
Fishing Vessels	90.81	90.81	90.81
General Cargo	151.92	151.92	151.92
Tugs	32.44	34.94	37.64
Oil Tankers	26.92	26.92	26.92
Bulk Carriers	202.79	218.46	235.35
Passenger Vessels	96.16	111.48	129.23
Offshore Vessels	92.28	92.28	92.28
Other Tankers	49.88	57.82	67.03
Container Ships	69.93	81.06	93.98
Hoppers/Dredgers	10.29	10.29	10.29
Refrg. Cargo Ships	40.84	40.84	40.84
RO-RO/Veh. Ships	43.69	47.07	50.71
LPG/LNG Tankers	20.73	24.03	27.86
Subtotal	**929**	**988**	**1,055**

6 to 8 MW

Market Segment	2001 - 2005	2006 - 2010	2011- 2015
Fishing Vessels	30.27	30.27	30.27
General Cargo	65.11	65.11	65.11
Tugs	0.00	0.00	0.00
Oil Tankers	53.83	53.83	53.83
Bulk Carriers	309.52	333.44	359.21
Passenger Vessels	26.23	30.40	35.24
Offshore Vessels	23.93	23.93	23.93
Other Tankers	55.42	64.25	74.48
Container Ships	78.67	91.20	105.72
Hoppers/Dredgers	6.17	6.17	6.17
Refrg. Cargo Ships	29.70	29.70	29.70
RO-RO/Veh. Ships	20.70	22.30	24.02
LPG/LNG Tankers	4.15	4.81	5.57
Subtotal	**704**	**755**	**813**

8 to 10 MW			
Market Segment	**2001 - 2005**	**2006 - 2010**	**2011- 2015**
Fishing Vessels	0.00	0.00	0.00
General Cargo	43.41	43.41	43.41
Tugs	0.00	0.00	0.00
Oil Tankers	62.80	62.80	62.80
Bulk Carriers	234.81	252.96	272.51
Passenger Vessels	26.23	30.40	35.24
Offshore Vessels	23.93	23.93	23.93
Other Tankers	38.79	44.97	52.13
Container Ships	104.89	121.60	140.96
Hoppers/Dredgers	4.12	4.12	4.12
Refrg. Cargo Ships	27.85	27.85	27.85
RO-RO/Veh. Ships	32.20	34.68	37.36
LPG/LNG Tankers	16.59	19.23	22.29
Subtotal	**616**	**666**	**723**

10 to 20 MW			
Market Segment	**2001 - 2005**	**2006 - 2010**	**2011- 2015**
Fishing Vessels	0.00	0.00	0.00
General Cargo	21.70	21.70	21.70
Tugs	0.00	0.00	0.00
Oil Tankers	206.35	206.35	206.35
Bulk Carriers	224.14	241.46	260.12
Passenger Vessels	87.42	101.34	117.48
Offshore Vessels	51.27	51.27	51.27
Other Tankers	16.63	19.27	22.34
Container Ships	270.97	314.12	364.16
Hoppers/Dredgers	6.17	6.17	6.17
Refrg. Cargo Ships	40.84	40.84	40.84
RO-RO/Veh. Ships	75.89	81.75	88.07
LPG/LNG Tankers	24.88	28.84	33.44
Subtotal	**1,026**	**1,113**	**1,212**

20 to 30 MW			
Market Segment	**2001 - 2005**	**2006 - 2010**	**2011- 2015**
Fishing Vessels	0.00	0.00	0.00
General Cargo	0.00	0.00	0.00
Tugs	0.00	0.00	0.00
Oil Tankers	71.77	71.77	71.77
Bulk Carriers	0.00	0.00	0.00
Passenger Vessels	61.19	70.94	82.24
Offshore Vessels	3.42	3.42	3.42
Other Tankers	0.00	0.00	0.00
Container Ships	96.15	111.46	129.22
Hoppers/Dredgers	4.12	4.12	4.12
Refrg. Cargo Ships	0.00	0.00	0.00
RO-RO/Veh. Ships	4.60	4.95	5.34
LPG/LNG Tankers	10.37	12.02	13.93
Subtotal	**252**	**279**	**310**

30 to 40 MW			
Market Segment	**2001 - 2005**	**2006 - 2010**	**2011- 2015**
Fishing Vessels	0.00	0.00	0.00
General Cargo	0.00	0.00	0.00
Tugs	0.00	0.00	0.00
Oil Tankers	0.00	0.00	0.00
Bulk Carriers	0.00	0.00	0.00
Passenger Vessels	17.48	20.27	23.50
Offshore Vessels	0.00	0.00	0.00
Other Tankers	0.00	0.00	0.00
Container ships	87.41	101.33	117.47
Hoppers/Dredgers	0.00	0.00	0.00
Refrg. Cargo Ships	0.00	0.00	0.00
RO-RO/Veh. Ships	0.00	0.00	0.00
LPG/LNG Tankers	2.07	2.40	2.79
Subtotal	**107**	**124**	**144**

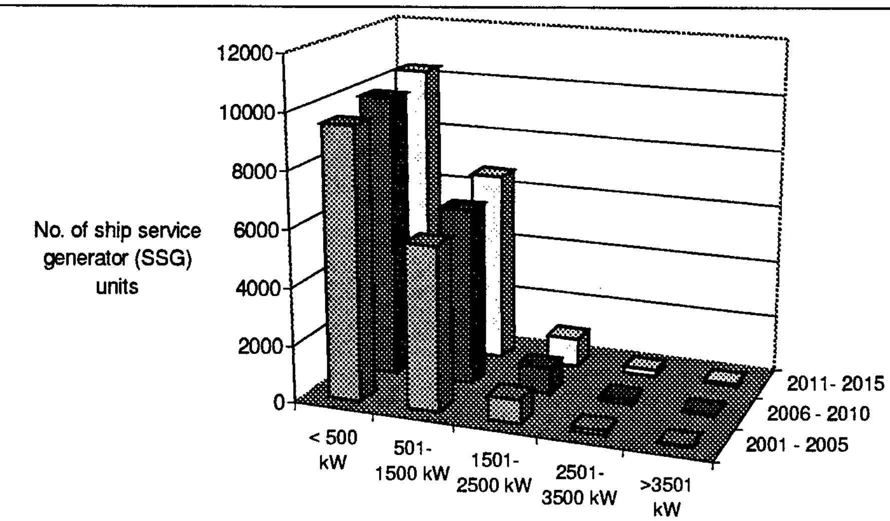
40 to 50 MW

Market Segment	2001 - 2005	2006 - 2010	2011- 2015
Fishing Vessels	0.00	0.00	0.00
General Cargo	0.00	0.00	0.00
Tugs	0.00	0.00	0.00
Oil Tankers	0.00	0.00	0.00
Bulk Carriers	0.00	0.00	0.00
Passenger Vessels	8.74	10.13	11.75
Offshore Vessels	0.00	0.00	0.00
Other Tankers	0.00	0.00	0.00
Container Ships	43.70	50.67	58.73
Hoppers/Dredgers	0.00	0.00	0.00
Refrg. Cargo Ships	0.00	0.00	0.00
RO-RO/Veh. Ships	0.00	0.00	0.00
LPG/LNG Tankers	0.00	0.00	0.00
Subtotal	**52**	**61**	**70**

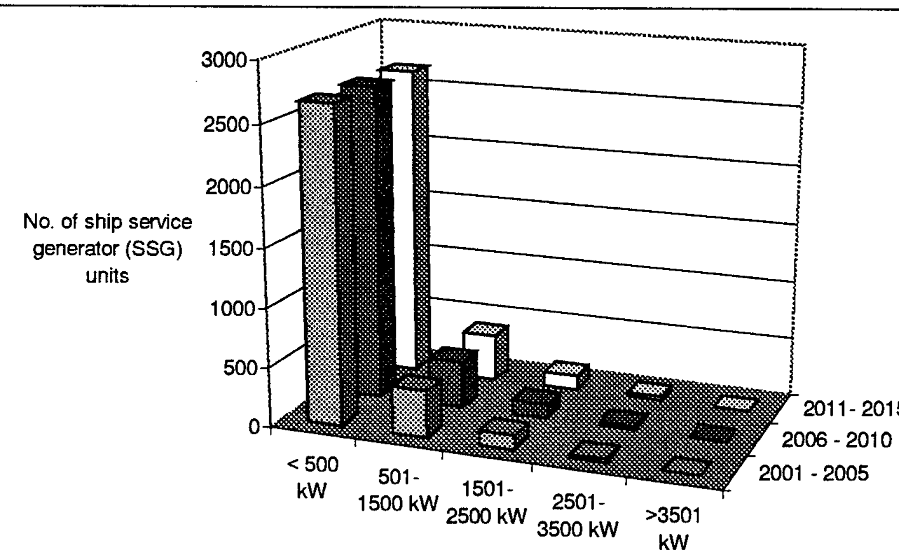
> 50 MW

Market Segment	2001 - 2005	2006 - 2010	2011- 2015
Fishing Vessels	0.00	0.00	0.00
General Cargo	0.00	0.00	0.00
Tugs	0.00	0.00	0.00
Oil Tankers	0.00	0.00	0.00
Bulk Carriers	0.00	0.00	0.00
Passenger Vessels	8.74	10.13	11.75
Offshore Vessels	0.00	0.00	0.00
Other Tankers	0.00	0.00	0.00
Container Ships	26.22	30.40	35.24
Hoppers/Dredgers	0.00	0.00	0.00
Refrg. Cargo Ships	0.00	0.00	0.00
RO-RO/Veh. Ships	0.00	0.00	0.00
LPG/LNG Tankers	0.00	0.00	0.00
Subtotal	**35**	**41**	**47**

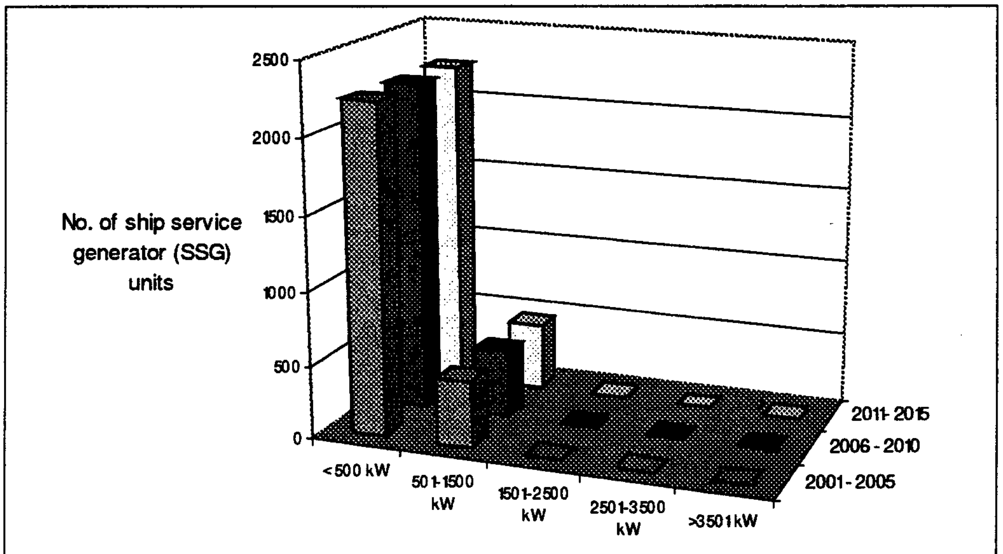
APPENDIX F.
SSG UNIT FORECAST FIGURES



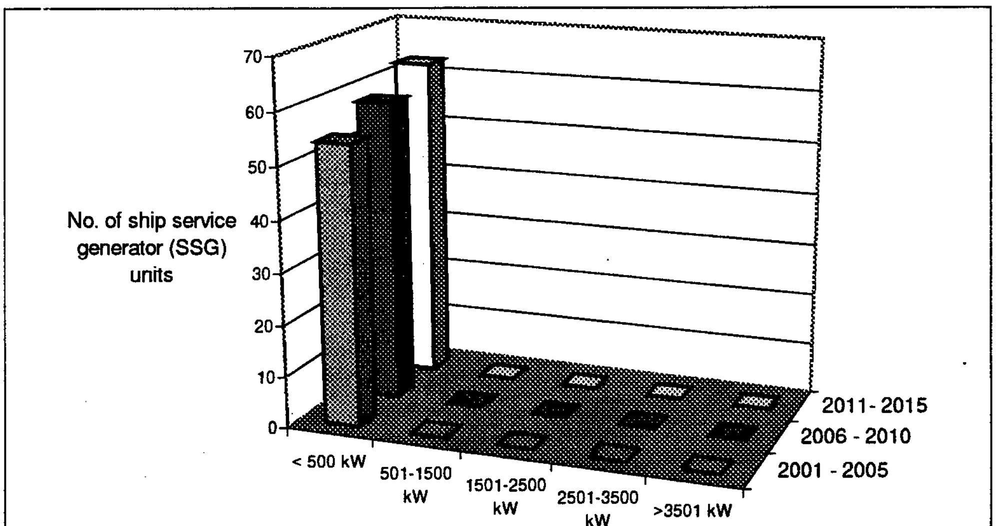
SSG Forecast -- ALL VESSEL TYPES



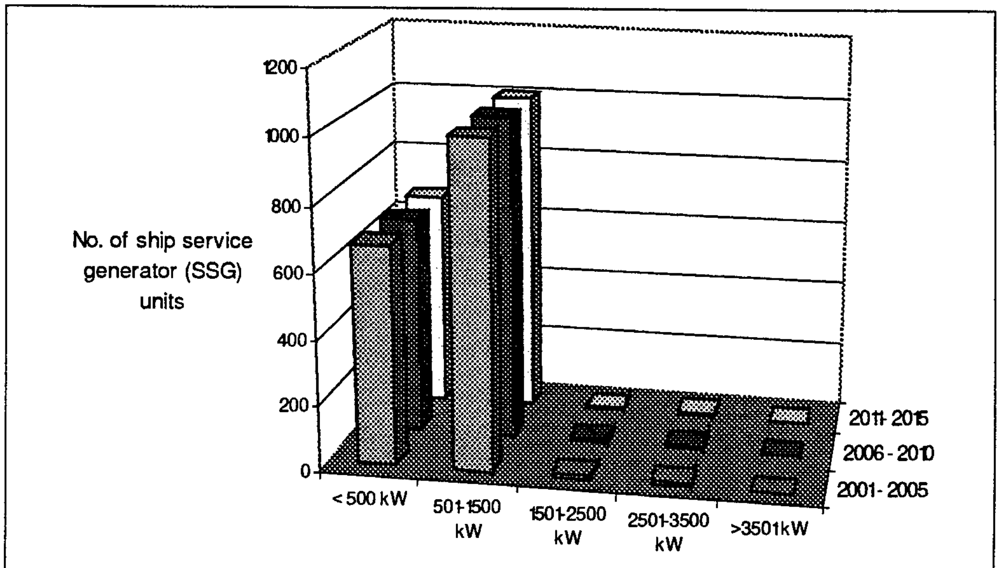
SSG Forecast for Fishing Vessels



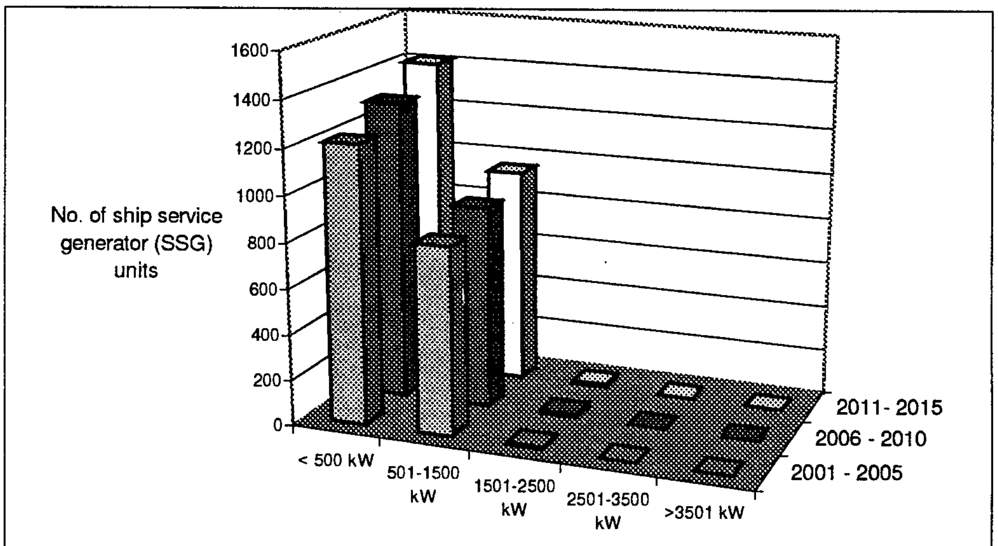
SSG Forecast for General Cargo Vessels



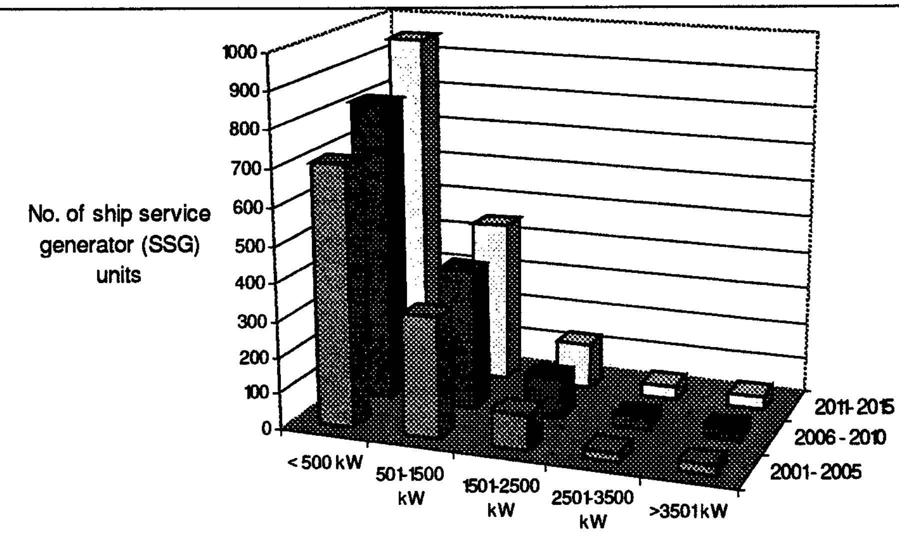
SSG Forecast for Tugs



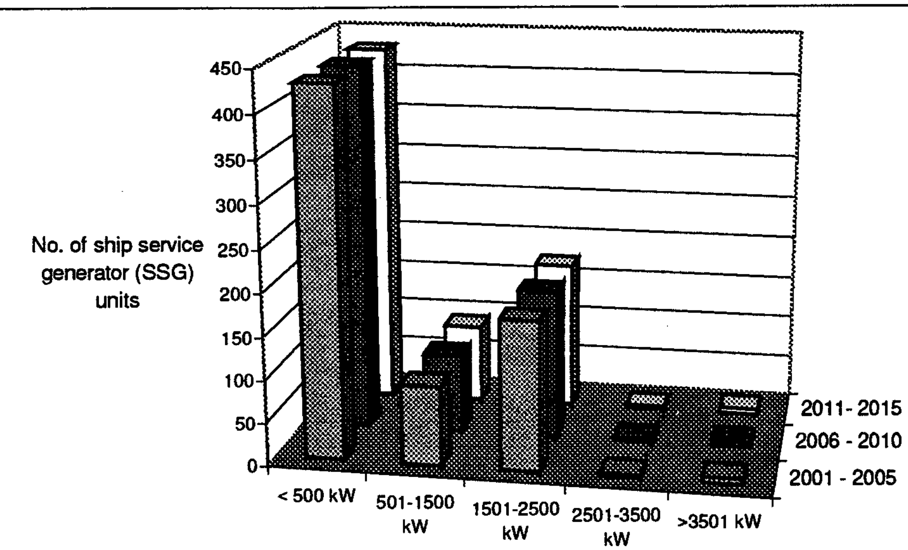
SSG Forecast for Oil Tankers



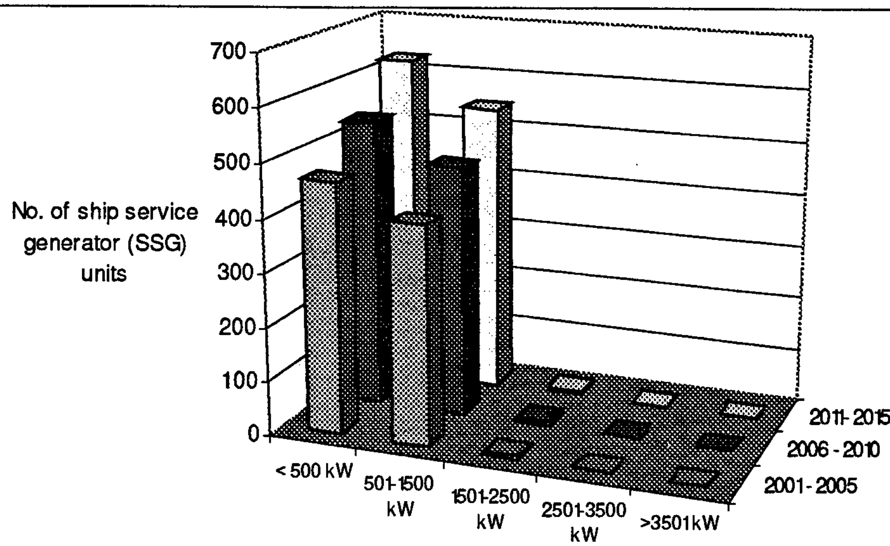
SSG Forecast for Bulk Carrier Vessels



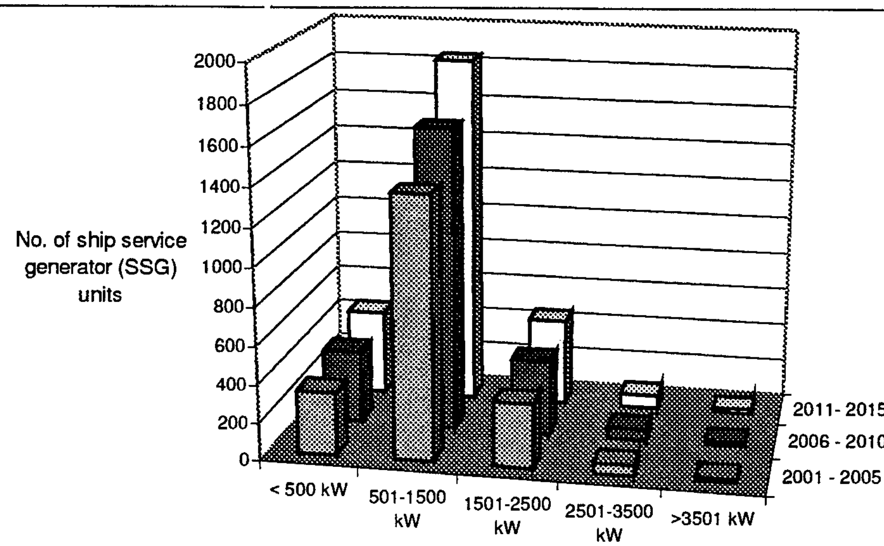
SSG Forecast for Passenger Vessels



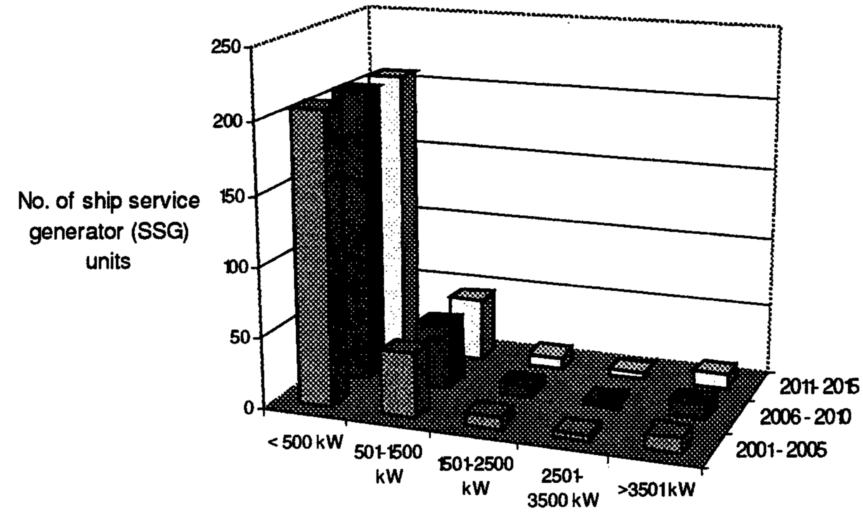
SSG Forecast for Offshore Vessels



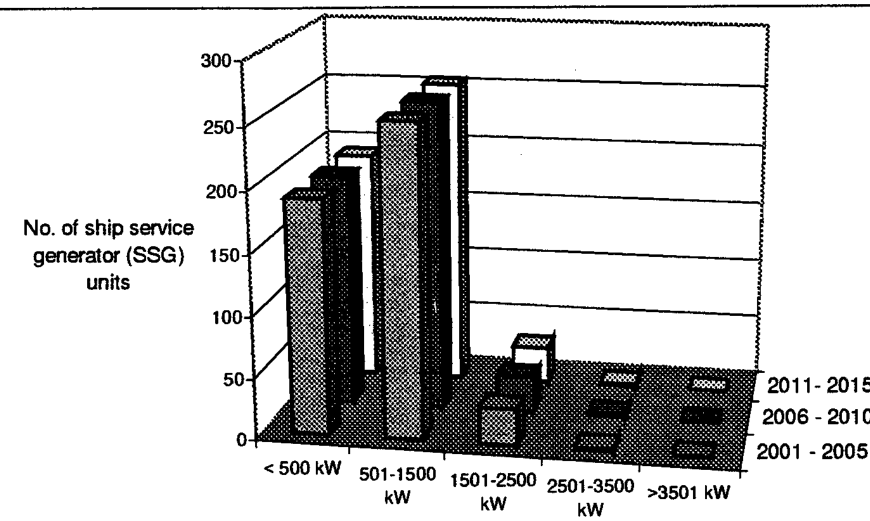
SSG Forecast for Other Tankers



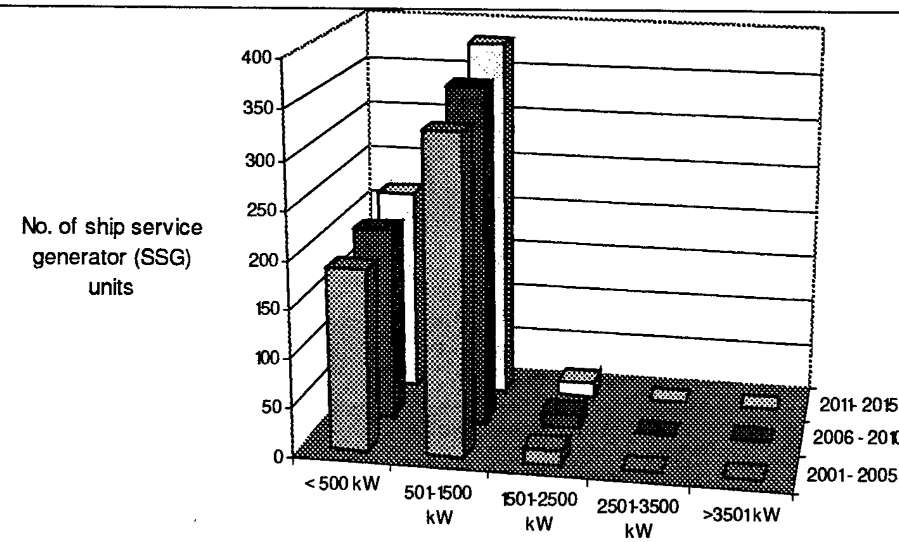
SSG Forecast for Container Vessels



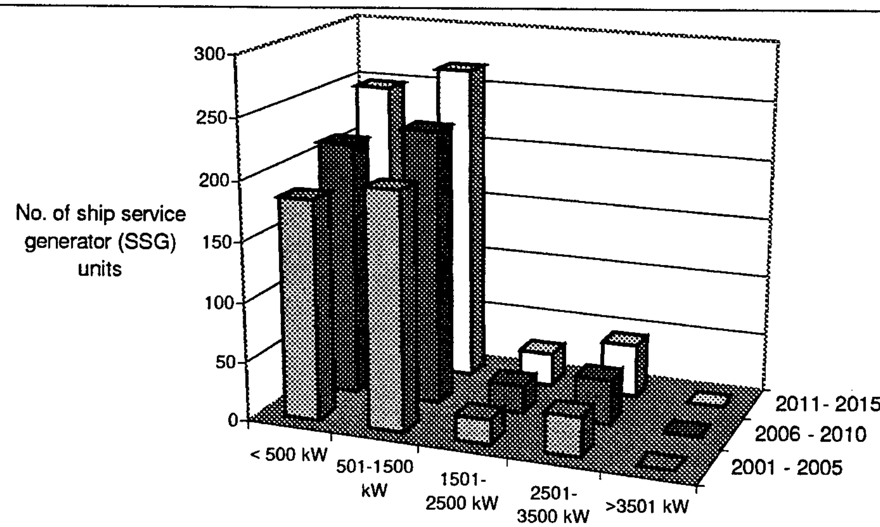
SSG Forecast for Hopper/Dredger Vessels



SSG Forecast for Refrigerator Vessels



SSG Forecast for RO-RO Vessels



SSG Forecast for LPG/LNG Tankers

[This page intentionally left blank.]

APPENDIX G.
SSG UNIT FORECAST DATA

< 500 kW

Market Segment	2001 thru 2005	2005 thru 2010	2011 thru 2015
Fishing Vessels	2,663.69	2,663.69	2,663.69
General Cargo	2,235.36	2,235.36	2,235.36
Tugs	54.06	58.24	62.74
Oil Tankers	672.88	672.88	672.88
Bulk Carriers	1,216.74	1,310.77	1,412.08
Passenger Vessels	708.09	820.87	951.61
Offshore Vessels	430.66	430.66	430.66
Other Tankers	465.52	539.66	625.62
Container Ships	332.15	385.05	446.38
Hoppers/Dredgers	207.83	207.83	207.83
Refrg. Cargo Ships	191.21	191.21	191.21
RO-RO/Veh. Ships	186.27	200.67	216.18
LPG/LNG Tankers	184.52	213.91	247.98
Subtotal	**9,549**	**9,931**	**10,364**

501 - 1500 kW

Market Segment	2001 thru 2005	2005 thru 2010	2011 thru 2015
Fishing Vessels	393.50	393.50	393.50
General Cargo	455.75	455.75	455.75
Tugs	0.00	0.00	0.00
Oil Tankers	1,004.84	1,004.84	1,004.84
Bulk Carriers	821.83	885.35	953.77
Passenger Vessels	332.19	385.10	446.44
Offshore Vessels	92.28	92.28	92.28
Other Tankers	404.56	468.99	543.69
Container Ships	1,372.31	1,590.88	1,844.27
Hoppers/Dredgers	45.27	45.27	45.27
Refrg. Cargo Ships	254.33	254.33	254.33
RO-RO/Veh. Ships	328.85	354.27	381.65
LPG/LNG Tankers	199.03	230.73	267.48
Subtotal	**5,705**	**6,161**	**6,683**

1501 - 2500 kW			
Market Segment	**2001 thru 2005**	**2005 thru 2010**	**2011 thru 2015**
Fishing Vessels	121.08	121.08	121.08
General Cargo	0.00	0.00	0.00
Tugs	0.00	0.00	0.00
Oil Tankers	8.97	8.97	8.97
Bulk Carriers	10.67	11.50	12.39
Passenger Vessels	96.16	111.48	129.23
Offshore Vessels	174.32	174.32	174.32
Other Tankers	5.54	6.42	7.45
Container ships	340.89	395.19	458.13
Hoppers/Dredgers	8.23	8.23	8.23
Refrg. Cargo Ships	29.70	29.70	29.70
RO-RO/Veh. Ships	13.80	14.86	16.01
LPG/LNG Tankers	20.73	24.03	27.86
Subtotal	**830**	**906**	**993**

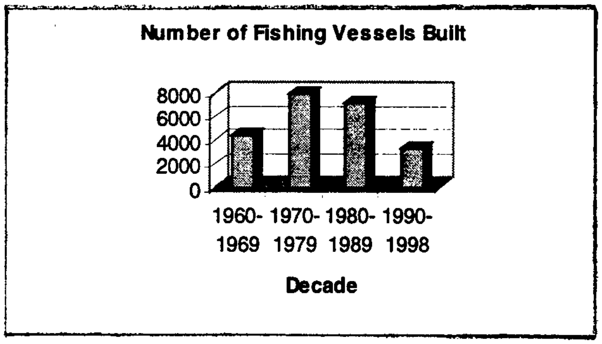
2501 - 3500 kW			
Market Segment	**2001 thru 2005**	**2005 thru 2010**	**2011 thru 2015**
Fishing vessels	30.27	30.27	30.27
General cargo	0.00	0.00	0.00
Tugs	0.00	0.00	0.00
Oil Tankers	8.97	8.97	8.97
Bulk carriers	0.00	0.00	0.00
Passenger vessels	26.23	30.40	35.24
Offshore vessels	3.42	3.42	3.42
Other tankers	0.00	0.00	0.00
Container ships	52.44	60.80	70.48
Hoppers/Dredgers	4.12	4.12	4.12
Refrg. cargo ships	1.86	1.86	1.86
RO-RO/Veh. ships	0.00	0.00	0.00
LPG/LNG tankers	33.17	38.46	44.58
Subtotal	**160**	**178**	**199**

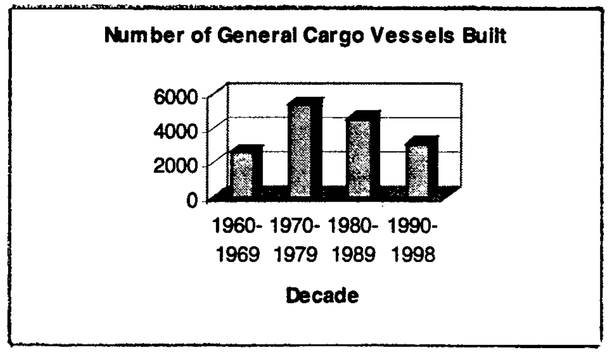
> 3501 kW			
Market Segment	**2001 thru 2005**	**2005 thru 2010**	**2011 thru 2015**
Fishing Vessels	0.00	0.00	0.00
General Cargo	0.00	0.00	0.00
Tugs	0.00	0.00	0.00
Oil Tankers	0.00	0.00	0.00
Bulk Carriers	0.00	0.00	0.00
Passenger Vessels	26.23	30.40	35.24
Offshore Vessels	6.84	6.84	6.84
Other Tankers	0.00	0.00	0.00
Container Ships	17.48	20.27	23.49
Hoppers/Dredgers	10.29	10.29	10.29
Refrg. Cargo Ships	0.00	0.00	0.00
RO-RO/Veh. Ships	0.00	0.00	0.00
LPG/LNG Tankers	0.00	0.00	0.00
Subtotal	**61**	**68**	**76**

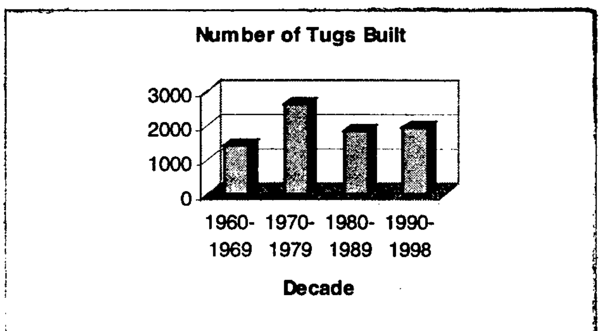
[This page intentionally left blank.]

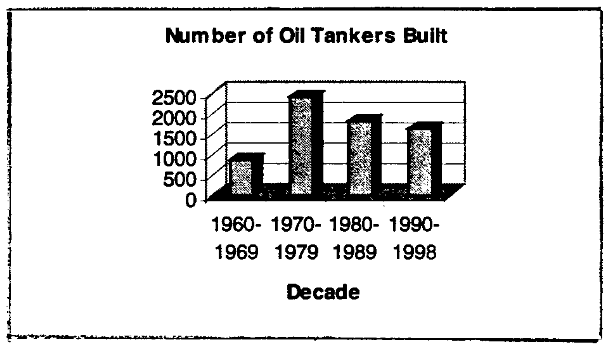
APPENDIX H.
HISTORICAL VESSEL COUNTS BY MARKET SEGMENT

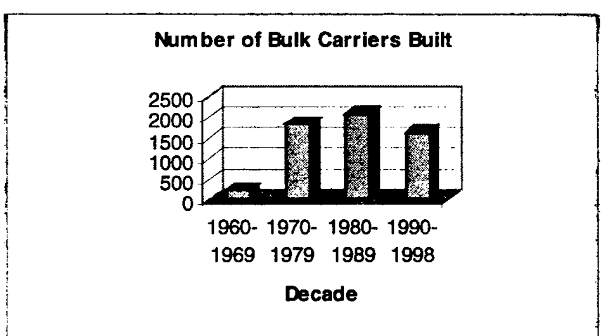
Built From 1960 through 1998

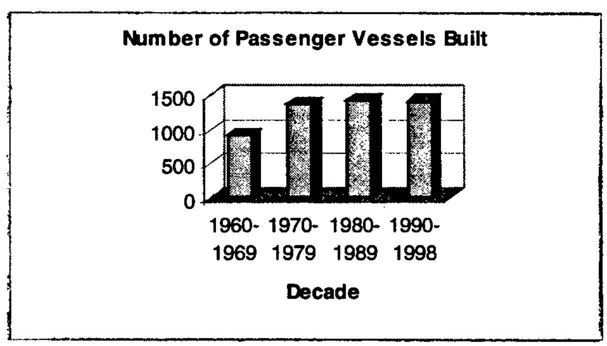


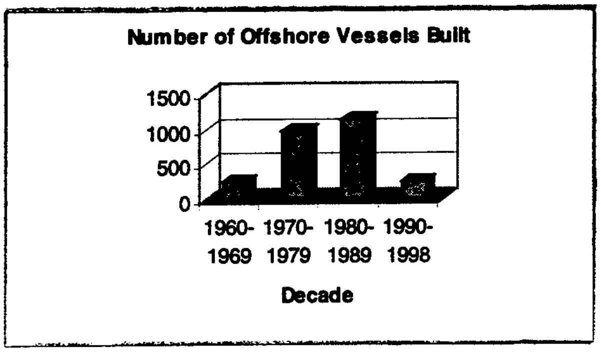


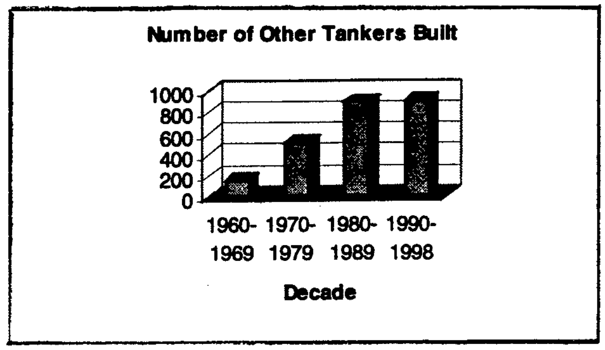


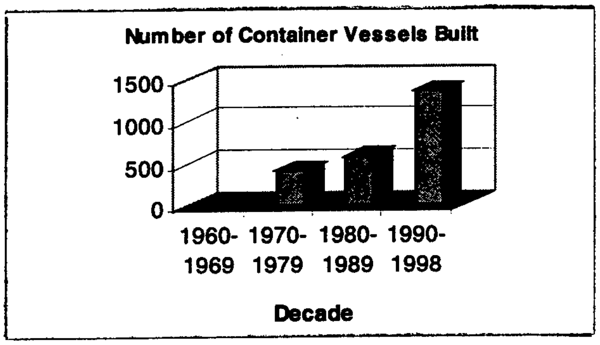


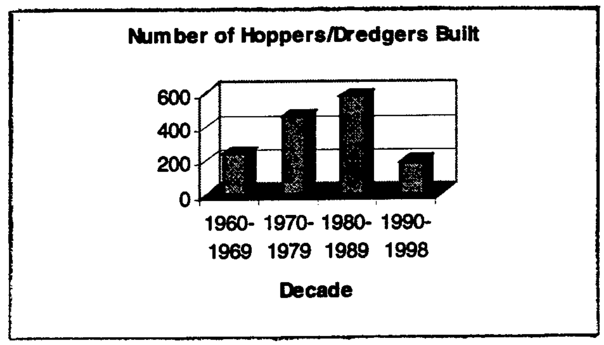


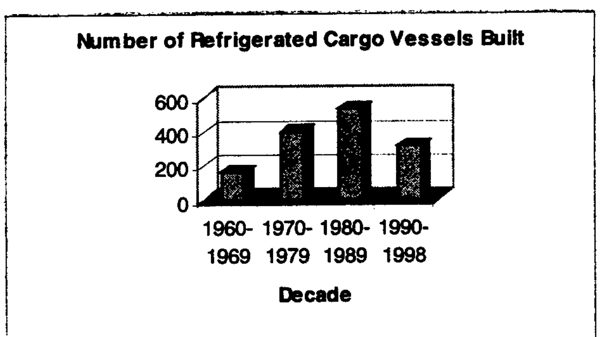


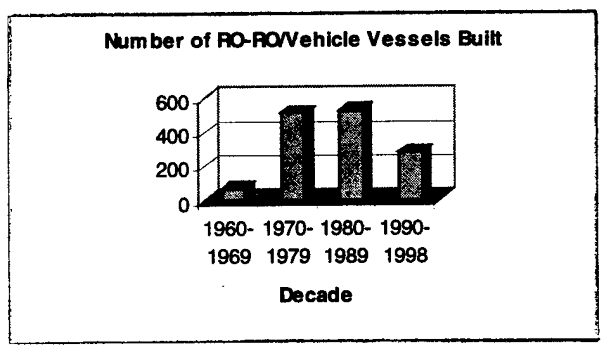

Number of Offshore Vessels Built
1500
1000
500
0
1960-1969
1970-1979
1980-1989
1990-1998
Decade

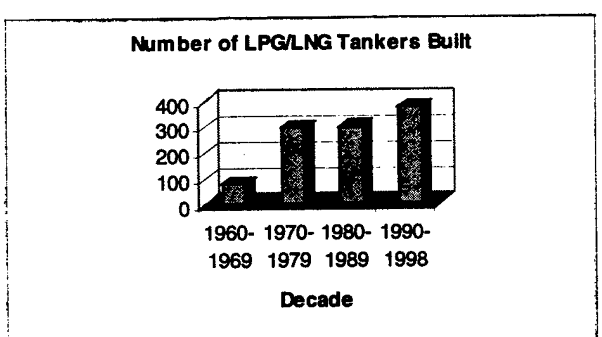

Number of Other Tankers Built
1000
800
600
400
200
0
1960-1969
1970-1979
1980-1989
1990-1998
Decade


Number of Container Vessels Built
1500
1000
500
0
1960-1969
1970-1979
1980-1989
1990-1998
Decade


Number of Hoppers/Dredgers Built
600
400
200
0
1960-1969
1970-1979
1980-1989
1990-1998
Decade


Number of Refrigerated Cargo Vessels Built
600
400
200
0
1960-1969
1970-1979
1980-1989
1990-1998
Decade


Number of RO-RO/Vehicle Vessels Built
600
400
200
0
1960-1969
1970-1979
1980-1989
1990-1998
Decade


Number of LPG/LNG Tankers Built
400
300
200
100
0
1960-1969
1970-1979
1980-1989
1990-1998
Decade